RISK BASED INSPECTION (RBI) TOOL DEVELOPMENT

NUR HAFIZAH BINTI MOHAMAD PISOL

CHEMICAL ENGINEERING
UNIVERSITI TEKNOLOGI PETRONAS
JULY 2009

CERTIFICATION OF APPROVAL

Risk Based Inspection (RBI) Tool Development

by

Nur Hafizah binti Mohamad Pisol

A project dissertation submitted to the
Chemical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(CHEMICAL ENGINEERING)

Approved by,

____

(Assoc. Prof. Dr. Azmi bin Mohd Shariff)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

July 2009

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

NUR HAFIZAH BINTI MOHAMAD PISOL

ABSTRACT

The cornerstone of plant integrity is ensuring that facilities are correctly designed, and operated and maintained within the equipment design envelopes. The profitability of the facilities is significantly impacted by the cost-effectiveness of inspection and maintenance strategies and programmes in place. Plant equipment is subjected to deterioration mechanisms and potential damage throughout their service life. Equipments inspection is very important in order to get the right information of the current conditions of the equipments. Risk Based approaches for managing inspection programs have emerged during the last decade as useful tools for managing risks associated with safety, health, environment and business. With quantitative RBI analysis, it is now possible to forecast inspection requirements, demonstrate the effects of inspection and facilitate the scheduling of inspection programmes. It is now widely accepted that the traditional time-based approach to planned plant inspection by competent person has a number of shortcomings. In particular, the use of fixed intervals between inspections may be too conservative and lacks the freedom to benefit from good operating experience. The introduction of goal setting legislation has facilitated a move towards risk based strategies, which focus inspection resources on parts of the plant where they will have the greatest benefit (IET, 2009). Throughout this project, RBI tool will be developed by using the provided guideline by American Petroleum Institute (API). RBI Tool frameworks for RBI qualitative risk analysis and RBI semi-quantitative risk analysis in this report are developed based on API methodology. The results from developed RBI Tool are validated by comparing them to the results of RBI from the industry. The risks between the two different RBI systems are different for the same case study. The different amount of information which is being supplied to the different RBI systems is identified as the main reason to the variation.

ACKNOWLEDGEMENTS

I would like to express my deep and sincere gratitude to my supervisor, Associate Professor Dr. Azmi Shariff for his kindness, guidance, advise, monitoring and encouragement. His wide knowledge and his logical way of thinking have contributed great value for me.

Warmly thanks to Mr. Wisnu Wahjusaputra, Aramis Asset Integrity Manager for his valuable advice and friendly help in sharing his knowledge on Risk Based Inspection. His extensive discussions around his work and interesting explorations in operations have been very helpful for this study.

A very deep appreciation also to Chemical Engineering Department of Universiti Teknologi PETRONAS management staffs for their concerns towards my difficulties and troubles during completing this project.

Loving thanks to my father, Mohamad Pisol bin Abdullah and my mother Hamidah binti Ismail. Without their encouragement and understanding it would have been impossible for me to finish this project and also my special gratitude to my siblings for their loving support.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Background

Risk Based Inspection (RBI) as a method for prioritising the inspection of plant has received considerable attention over the last few years and methods have been developed nationally, for example by the American Petroleum Institute (API) and by a number of private organisations, particularly in the petrochemical industry. A co-ordinated approach to these developments is underway in Europe (RIMAP).

Risk of an accident has two components, likelihood and consequence. Risk may be expressed as calculated numerical value. More effective way of presenting risk is to plot probability and consequence of failure on a risk matrix. For risk management there are several steps can be done for the high risk equipment such as inspection maintenance and repair improvement, reduction of consequences, reduction of probability of failure or decommission. Otherwise, only monitoring is required. Inspection is an activity intended to limit risk must reduce one or both of the risk components.

RBI is one of the inspection methods and it uses risk as a basis for prioritizing and managing the efforts of an inspection program or the quantitative decision making technique for cost-optimum inspection planning based on risk comprising the probability of failure and consequence (API 581, 2000). RBI objectives are to focus on what to inspect through the prioritization of high risk components, when to inspect by determining degradation mechanisms and how to inspect through the selection of best inspection method. In comparison, traditional "time-based inspection" has only one date and fixed inspection requirements for all equipment.

Many plants start to implement RBI because it gives more accurate result in term of the reliability of the inspection programme. This is because; most of existing inspection programmes are implemented only based on likelihood or consequence of factor. Through RBI, the severity of consequence level can be reduced through the right mitigation action in which is cost effective.

RBI also helps the engineers to focus more on high risk equipments rather than to waste time, energy and cost on low risk equipments.

The consequence modeling procedure for RBI is a greatly simplified approach to a relatively complex discipline. Because of the level of simplification, a large number of assumptions are implicit in the procedure in addition to the assumptions that would be part of a more in-depth analysis. The important assumptions related to the simplified approach are as below:

i. The consequence area does not reflect where the damage occurs.
ii. The use of a fixed set of conditions for meteorology and release orientations is a great simplification over detailed consequence calculation because these factors can have a significant impact on the result.
iii. The use of the standardised event trees for consequence outcomes and ignition probabilities is a limitation of the RBI method. These factors are very site-specific, and the user needs to realize that they are chosen to reflect representative condition for petrochemical industry.

RBI is now known as a well-known method to design inspection programmes but it has only been standardised for pressure systems by API 581. When it comes to such items as topside structures, there is no such reference.

1.2 Problem Statement

In asset and services core management, one of important elements is risk analysis and risk management. This element involves maintenance strategy in which requires RBI for maintenance engineering co-ordination. However, most of industries do not implement RBI due to its high cost in buying RBI software. API has published Risk Based Inspection Based Resource Document in which has provided a complete methodology for RBI programme. This methodology can be used to develop RBI Tool.

1.3 Objective

To develop a cost-effective Risk Based Inspection (RBI) Tool prototype by using published methodology from API 581.

1.4 Scope of Study

This tool is developed by using Visual Basic Application (VBA). This RBI Tool consists of qualitative and semi-quantitative level analysis. This prototype is developed based on recommended methodology from API. The methodology only covers for pressurised equipments and associated components.

CHAPTER 2

LITERATURE REVIEW

RBI considers the probability of failure and its consequences. The technique is intended to get better value for money from inspection. RBI is a technique, which is currently being adopted by sectors of industry, particularly the refining and petrochemical sectors, to underpin and direct planned plant inspection. It is claimed to offer the prospect of cost savings resulting from better targeting resources. RBI recognizes that there is little point to spending good money, for example, on very frequent inspection of something that is very unlikely to fail, or if it did fail would have little financial or safety consequence. In line with the principles of ALARP (as low as reasonably practicable) the money saved may be better spent elsewhere. Savings can also arise from reduced direct inspection costs (IET, 2007). Risk-Based Inspection Risk Based Inspection (RBI) studies define inspection programs. Information is generated on the types of damage that may be expected, appropriate inspection techniques to be used, where to look for potential damage, and how often inspections should take place. Risk Based Inspection (RBI) is regarded as cost effective alternative to traditional inspection. Risk Based Inspection (RBI) is used for planning and implementation of inspection and maintenance programmes. History tells that 80% of the risk industrial plants in general are related to 20% of the pressure equipment. To be more efficient with inspections and maintenance, it is useful to identify this 20% higher risk assets.

PETRONAS has been successful in implementing RBI for platform structures and for mechanical piping. Number of planned comprehensive inspection for platform structures have been reduced from 117 to only 59 after the implementation of RBI procedure (A.Raman, 2007).

Traditional inspection planning is time based. All equipments received essentially the same inspection effort. The inspections focused primarily on visual examination which means that it's incapable of detecting many of the most likely degradation mechanisms such as stress corrosion cracking (SCC), embrittlement, hydrogen damage, creep and etc. Sometimes, hydro-testing was specified in some instances. Even though it serves as a proof test, but it has little value in determining deterioration rate and it may actually initiate corrosion. It does not prove fitness for continued service. Moreover the inspection method focused on vessels but most failures are associated with piping.

There are lot of companies have taken initiative by developing in-house RBI tool. These can provide the RBI team with a model for the assessment and ranking of risk. Packages vary in complexity but generally follow the semi-quantitative risk assessment methodology. The RBI software packages have been successfully developed by the following suppliers:

- Akzo Nobel
- Det Norsk Veritas (DNV)
- The Welding Institute (TWI) has developed **RiskWise**
- Tischuk has developed **T-OCA**
- LMP Technical Services has developed **PRIME-RBI Module**

A survey of approximately 50 UK organisations showed that approximately half were using an approach to plant inspection based on risk (W. Geary, 1999). It was clear however, that a wide range of systems were in use including commercial software packages and in-house systems specific to individual plants.

CHAPTER 3

METHODOLOGY

3.1 Risk Analysis

At its core, RBI is a hybrid technique that combines the two disciplines of risk analysis and mechanical integrity (API 580, 2002). Some of the techniques of RBI are similar to those seen in traditional risk analysis, but the two are interchangeable. In its elemental form, a risk analysis is comprised of five tasks:

i. System definition
ii. Hazard identification
iii. Probability assessment
iv. Consequence analysis
v. Risk results

Some of the phases of a risk analysis are treated differently in a RBI program. For example, while hazard identification is a critical step in a traditional risk analysis, the RBI program focuses on the pressure boundary of a unit, and it assumes that failures are due to identifiable mechanisms of degradation in that boundary. Secondary causes of leak, such as instrument failures or human errors, are included implicitly in the RBI program's treatment of management systems, while a traditional risk analysis would account for these failures in explicit terms. The major focus of a traditional risk analysis is to evaluate a variety of scenarios that may lead to undesirable outcomes. Both the likelihood and the magnitude of these outcomes are estimated and displayed as results. In a risk analysis, a scenario represents the set of events that can result in an undesirable outcome. Depending on the nature of the process and the detail of the study, a risk analysis may include thousands of different scenarios. The risk analysis would evaluate both the likelihood and the consequence of the set of events in each scenario. In RBI, likelihood and consequence are also evaluated, but for a carefully defined and limited number of scenarios.

The probability assessment is conducted to estimate the probability of occurrence for the scenarios identified. If a scenario occurs fairly frequently, it is best to use historical data to estimate the event's probability. However, it is often the case in the petroleum industry that the events of concern are so rare that sufficient data does not exist to estimate their probability based on historical data alone. When historical data is lacking, a building-block approach is used. Probability estimates for all elements of the scenario are obtained and combined to predict overall scenario probability. The most common measure of probability for a scenario is its frequency. Frequency can be used for a single event or a series of events. Typically, a year is used as the standard time interval for a frequency analysis. To obtain the frequency of the scenario ($F_{Scenario}$), multiply the frequency of leak (F_{Leak}) by the probability of all events that follow ($P_{Outcome}$). The resulting likelihood is the scenario's frequency. The mathematical representation of the likelihood of the sequence, in terms of frequency, is shown below:

$$F_{Scenario} = F_{Leak} x P_{Outcome} \qquad \textit{(Equation 1)}$$

The consequence of release from process equipment or pipework vary depending on such factors as physical properties of the material, its toxicity or flammability, weather conditions, release duration and mitigation actions. The effects may impact plant personnel or equipment, population in the nearby residences, and the environment. Hazardous consequences are estimated in five phases:

1. Discharge
2. Dispersion

3a. Flammable Effects
3b. Toxic Effects
3c. Environmental Effects

Depending on the material released, only one of the three effects (3a-3c) is usually calculated, although all of them may be possible with releases of certain mixtures. In traditional risk analysis, there is no single way to measure or present an estimate of the risk of operating a chemical process. Historically, a number of measures have been used to express risk in the context of a risk analysis. Risks to people are normally presented in one of three ways:

i. Risk Indices
ii. Individual Risk Measures
iii. Societal Risk

The consequence analysis in an RBI program is performed to aid establishing a relative ranking of equipment items on the basis of risk. An overview of the RBI consequence calculation is shown in Figure 1.

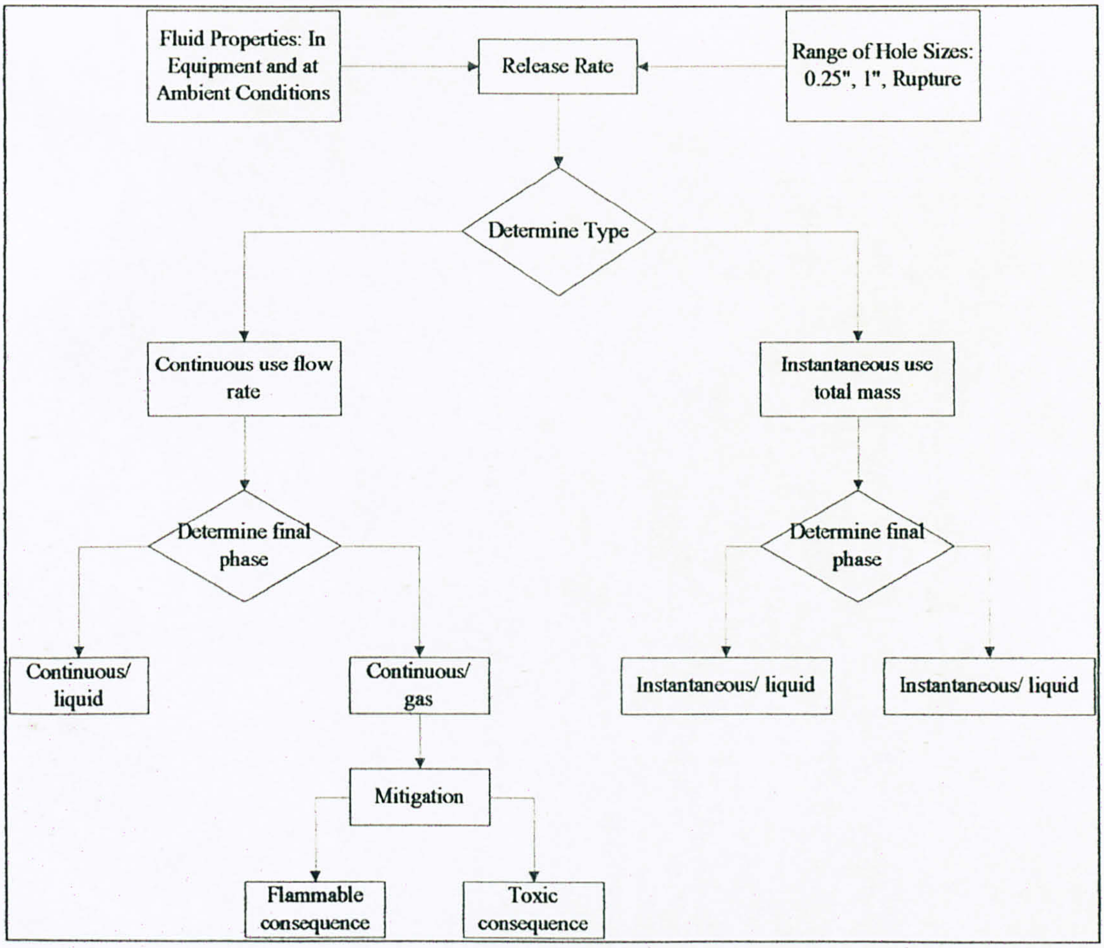


Figure 1: Overview of RBI Consequence Calculation

The consequences of releasing hazardous fluid are estimated in following steps:

[1] Determining representative fluid and its properties

[2] Selecting a set of hole sizes, to find the possible range of consequences in the risk calculation

[3] Estimating the total amount of fluid available for release

[4] Estimating the potential release rate

[5] Defining the type of release, to determine the method used for modeling the dispersion and consequence

[6] Selecting the final phase of the fluid, i.e., liquid or a gas

[7] Evaluating the effect of post-leak response

[8] Determining the area potentially affected by the release, or the relative cost of the leak due to down time or environmental clean up

3.2 Qualitative Level in RBI Tool

RBI Tool is developed by using the simple workbook approach in API 581 with the philosophy that a typical refinery can be assessed in a few hours.

In qualitative level for RBI Tool, the risk is used to examine refinery and petrochemical operations for process hazards associated with pressure equipment integrity. The qualitative is similar to that of the quantitative analysis except that the qualitative approach requires less detail and is far less time consuming. The results are not as precise as those of the quantitative analysis and it can be used as basis for prioritizing a risk based inspection program.

The analysis can be performed at any of the following levels:

i. An operating unit
ii. A major area or functional section in an operating unit
iii. A system

The procedures have three functions:

i. Screening the units within the site to select the level of analysis needed and to ascertain the benefit of further analysis
ii. Rating the degree of risk within the units and assigning them to a position within a risk matrix
iii. Identifying areas of potential concern at the plant, which may merit enhanced inspection programs

The analysis first determines a factor representing the likelihood of failure within the area, then a factor for the consequences. The two are then combined in the risk matrix to produce a risk rating for the unit.

In likelihood category, there are six factors need to be evaluated and each factor is weighted, and their combination results in the likelihood factor. This factor is plotted on the vertical axis of the risk matrix. The six subfactors that make up the likelihood category are as follows:

i. Amount of equipment (Equipment Factor, EF)
ii. Damage mechanisms (Damage Factor, DF)
iii. Appropriateness of inspection (Inspection Factor, IF)
iv. Current equipment condition (Condition Factor, CCF)
v. Nature of the process (Process Factor, PF)
vi. Equipment design (Mechanical Design Factor, MDF)

The sum of these six components establishes the overall likelihood factor. The likelihood category is then assigned based on the overall likelihood factor.

Table 1: Assignment Value of Likelihood Category for Qualitative Level Analysis

Likelihood Factor	Likelihood Category
0 to15	1
16 to 25	2
26 to 35	3
36 to 50	4
51 to 75	5

For consequence category, there are two major potential hazards are considered:

i. Fire and explosion and
ii. Toxic risk.

In determining the toxic consequence, RBI considers only the acute effects. These determinations are usually made for each chemical. Many chemicals, however, exhibit a predominate risk (fire or explosion or toxicity); thus if the predominant risk for a given chemical is known, it is necessary to determine only the factor for that risk not for both. The consequence that generates the highest letter category is used to determine the qualitative risk rating. If there are several chemicals present in relatively large percentages in the area, the user should conduct the exercise several times; once for each of the chemicals present in relatively large proportions. A good rule of thumb is to review the chemicals with high health consequence, plus those that comprise at least 90-95% of the total mass of chemicals in the area.

The damage consequence category is derived from a combination of five elements that determine the magnitude of a fire and/or explosion hazard:

i. Inherent tendency to ignite (Chemical Factor, CF)
ii. Quantity that can be released (Quantity Factor, QF)
iii. Ability to flash a vapor (State Factor, SF)
iv. Possibility of auto-ignition (Auto-Ignition Factor, AF)
v. Effects of higher pressure operations (Pressure Factor, PRF)

vi. Engineered safeguards (Credit Factor, CRF)

vii. Degree of exposure to damage (Damage Potential Factor, DPF)

The sum of these seven components establishes the overall damage consequence factor. The damage consequence category is then assigned based on the overall damage consequence factor.

Table 2: Assignment Value of Damage Consequence Category for Qualitative Level Analysis

Damage Consequence Factor	Damage Consequence Category
0-19	A
20-34	B
35-49	C
50-79	D
>70	E

The health consequence category is derived from the following elements that are combined to express the degree of a potential toxic hazard in a unit:

i. Quantity and toxicity (Toxic Quantity Factor, TQF)

ii. Ability to disperse under typical process conditions (Dispersibility Factor, DIF)

iii. Detection and mitigation systems (Credit Factor, CRF)

iv. Population in vicinity of release (Population Factor, PPF)

The sum of these seven components establishes the overall damage consequence factor. The health consequence category is then assigned based on the overall damage consequence factor.

Table 3: Assignment Value of Health Consequence Category for Qualitative Level Analysis

Health Consequence Factor	Health Consequence Category
<10	A
10 to 19	B
20 to 29	C
30 to 39	D
>40	E

The likelihood category rating and the highest rating form either the damage or the health consequence categories are used to place each unit within a five-by-five risk matrix, shown in Figure 2. When results are plotted on the matrix, they give an indication of the level of risk for the unit being evaluated. When the qualitative analysis has included several materials or a multi-component mixture, the unit receiving the highest risk component will be the best indicator of whether further evaluation is necessary, as well as the urgency of that evaluation.

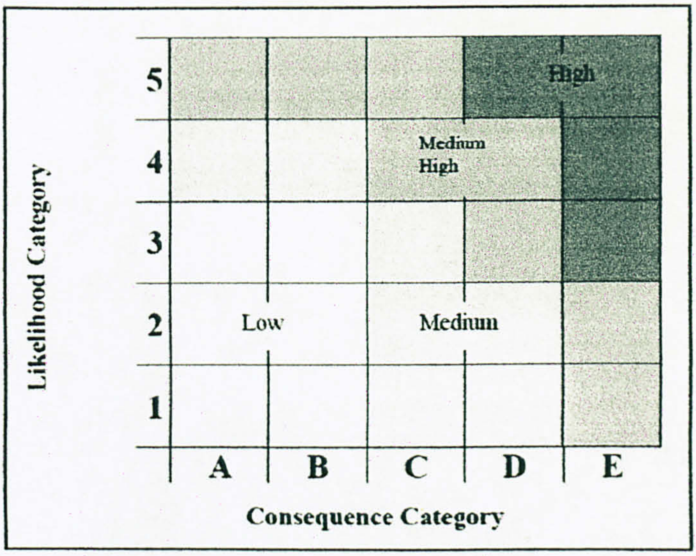


Figure 2: Five-by- Five Risk Matrix

The risk matrix results can be used to locate areas of potential concern and to decide which portions of the process unit need the most inspection attention or other methods of risk reduction. It can also be used to decide whether a full quantitative study is justified. The shadings are not symmetrical, as they are based on the assumption that, in almost every case, the consequence factor will carry more weight in determining total risk than will the likelihood component. Without the shading, it seems clear that, as the plotted value for the likelihood and consequence categories moves toward the upper right of the matrix, the amount of risk increases. Companies generally will develop and apply their own criteria to determine when it becomes necessary to perform a quantitative RBI or adjust their inspection practices.

3.3 Semi-Quantitative Level in RBI Tool

Semi-quantitative analysis is simplified approach than quantitative analysis (determination inventory amounts, excluding business interruption & environmental consequence, considering only Technical Module Sub-Factor (TMSF) for likelihood analysis). The semi-quantitative analysis typically requires the same data as quantitative analysis but generally not as detailed. For example, the fluid volumes may be estimated. Although the precision of the analysis may be less, the time required for data gathering and analysis will be less too.

The petrochemical industry lacks a specific experience database in regards to failure frequency categorized by equipment type and specific process environment. As a result, there is a modification of generic failure frequency for each equipment type by a factor related to the type of potential in-service degradation occurring in the particular service and the type of inspection and/ or monitoring performed. The term "Technical Module" is to describe the methodology by which this modification factor is calculated. The following Technical Modules is embedded in the developed system:

i. Thinning
ii. Stress Corrosion Cracking (SCC)
iii. High Temperature Hydrogen Attack (HTHA)
iv. Furnace Tubes
v. Mechanical Fatigue (piping only)
vi. Brittle Fracture
vii. Equipment Linings
viii. External Damage

These Technical Modules cover the general procedures for handling the degradation type and detailed supplemental technical information for specific degradation mechanisms. The Technical Modules have built into them the ability for updating the modification factor (referred to as the "Technical Module Subfactor or TMSF") based on the most recent inspection and monitoring information available. If more than one of the general damage types are potentially present, the individual TMSF are additive. For example:

$$TMSF_{Thinning} + TMSF_{SCC} + TMSF_{HTHA}$$

If the Furnace Module is used for determination of $TMSF_{Furnace}$, the $TMSF_{Furnace}$ should replace $TMSF_{Thinning}$, for example:

$$TMSF_{Furnace} + TMSF_{SCC} + TMSF_{HTHA}$$

The overall equation for determining the cumulative TMSF is:

$$TMSF_{Final} = TMSF_{Thinning} + TMSF_{SCC} + TMSF_{HTHA} + TMSF_{Fatigue} + TMSF_{BF} + TMSF_{Lining}{}^{*} + TMSF_{External} \qquad \textit{(Equation 2)}$$

** The smaller of $TMSF_{Lining}$ or $TMSF_{Thinning}$ should be used if both are active.*

The Technical Modules are intended to support the RBI methodology by providing a screening tool to determine inspection priorities, and to optimize inspection efforts. The Technical Modules do not provide a definitive "Fitness for Service" assessment of the equipment involved. The basic function of the module is to statistically evaluate the amount of damage that may be present and the effectiveness of inspection activity. The Technical Module Subfactors calculated are based on probability theory, but are not intended to reflect the actual probability of failure for the purposes of reliability analysis. The Technical Module Subfactors calculated are based on probability of failure for the purposes of reliability analysis. The Technical Module Subfactors reflect a relative level of concern about the equipment based on the assumptions of the module.

All equipments should be considered for thinning and SCC. Simple screening questions at the beginning of HTHA, Furnace, Brittle Fracture, Mechanical Fatigue, External Damage, and Lining modules are used to determine whether these modules apply. The purpose of the technical modules is to determine a technical module subfactor based on equipment specific knowledge such as measured corrosion rate to SCC based on experience and/or inspection history.
In consequence category, the consequences of releasing a hazardous material are considered and estimated in five distinct steps:

i. Estimate the release rate or the total mass available for release
ii. Determine if the fluid is dispersed in a rapid manner (instantaneous) or slowly (continuous)
iii. Determine if the fluid disperses in atmosphere as a liquid or gas
iv. Estimate the impacts of any mitigation system
v. Estimate the consequences

Instantaneous releases are those that empty the contents of a vessel in a relatively short period of time, as in the case of brittle failure of a vessel. Continuous releases are those that occur over a long period of period at relatively constant rate. In the context of the RBI analysis, consequence refers to adverse effects on people, equipment, and the environment as a result of outcome. The actual outcome of a release depends on the nature and properties of the material released.

One major simplification in consequence analysis for semi-quantitative level is in determination of inventory amounts. Inventories may be estimated on an order of magnitude basis using the following guidelines. The inventories can be selected from one of five "order of magnitude" categories as shown in Table 4.

Table 4: Inventory Category Ranges

Category	Range	Value used in calculations
A	100 to 1000 lbs	500
B	1000 to 10000 lbs	5000
C	10000 to 100000 lbs	50000
D	100000 to 1000000 lbs	500000
E	1000000 to 10000000 lbs	5000000

The user can select the category based on judgmental evaluation for each category as outlined in Table 5.

Table 5: Description of Inventory Categories

Category	Qualitative Description
A	The release will result in less than total deinventory of the equipment item being evaluated
B	The release will result in total deinventory of the equipment item being evaluated
C	The release will result in total deinventory of the equipment item being evaluated, plus one to ten other equipment items
D	The release will result in total deinventory of the equipment item being evaluated, plus ten or more other equipment items
E	The release will result in total deinventory of the unit

The person performing the analysis still has the option to use any value for the inventory. For example, if the inventory has been calculated, this value may be entered. The consequence area is calculated for each hole size. To calculate a single overall consequence of failure for each equipment item, a "Likelihood Weighted" average area is calculated. This is done by first multiplying the consequence area for each hole size by the ratio of the "generic" frequencies for all hole sizes. (See Equation 3)

$$\text{Likelihood Weighted Area} = \frac{FREQn_{n=4}}{FREQn_{n=1}} xAREAn \qquad \textit{(Equation 3)}$$

This ratio determines the "weight" to be given to the calculation area for each hole size depending on the relative likelihood of the hole relative to other holes. In this approach, the value of each "generic" frequency does not matter, only the relative values of each versus the others. The weighted are thus calculated for each hole size is the summed to produce a single consequence area value. (See equation 4) This value can be considered to be most likely affected area if many events were observed that follow the distribution of generic hole sizes used.

$$\text{Likelihood Weighted Average} = \sum_{n=1}^{n=4} AREAnx \frac{FREQn}{\sum_{n=1}^{n=4} FREQn} \qquad \textit{(Equation 4)}$$

The conversion of the likelihood weighted average area to a consequence category is accomplished through a simple assignment of categories to area values. It is possible, depending on the assignments chosen, to have an area associated with any category, according to the needs of the study. Table 6 is magnitude assignment of areas to categories.

Table 6: Consequence Area Categories

Consequence Category	Likelihood Weighted Average Area
A	<10ft2
B	10-100ft2
C	100-1000ft2
D	1000-10000ft
E	>10000ft2

Likelihood analysis will be determined by the technical module subfactor. This is the only subfactor that is directly affected by inspection and that will form the basis for an inspection plan. The conversion of technical module subfactor to a likelihood category is accomplished through a simple assignment of categories to subfactors values. A simple order of magnitude assignment was chosen and is illustrated in Table 7.

Table 7: Technical Module Subfactor Conversion

Likelihood Category	Technical Module Subfactor
1	<1
2	1-10
3	10-100
4	100-1000
5	>1000

The risk analysis for semi-quantitative approach is a straight forward assignment of likelihood and consequence to their appropriate categories and placing them in the 5x5 matrix. Different areas of the matrix are shaded to illustrate "High", "Medium", "Medium High" and "Low" categories of risk. These assignments are shown in Figure 2.

3.4 Inspection Plan Development

This strategy is aimed to deliver timely inspections that bring valuable information in the form of inspection results. The reduction in component condition uncertainty and increase in predictability of deterioration rates translate directly into a reduction in the likelihood of failure. The inspection strategy must address the following areas:

i. Which items are susceptible and where are they located?
ii. What inspection methods or tools must be adopted in order to deliver the required inspection result?
iii. How effective are the selected inspection methods at detecting the perceived degradation mechanisms?
iv. How much inspection is required in order to assure the target inspection effectiveness?
v. What frequency of inspection is required for each inspectable unit or component?

Potential failure modes should be estimated before inspection methods are selected. For each failure mode, the potential degradation mechanisms that can cause those failures are identified. The evaluation of such mechanisms should consider the type and rate (time dependency) of degradation that may be likely.

A preliminary evaluation of the applicable degradation mechanisms and deterioration rates may have been performed during the likelihood estimation in the risk prioritization step. During this step, those evaluations should be reconsidered for the higher risk items, and perhaps a more detailed assessment may be necessary. Once the degradation mechanisms have been accurately assessed, the selection of an inspection method can be successfully achieved. It is important to consider that there are many inspection techniques and testing methods available to accurately assess component integrity. Appendix C provides a listing of inspection methods available to assess common degradation mechanisms.

3.5 RBI Tool Frameworks

Both RBI qualitative and semi-quantitative risk analysis are developed based on methodology from Risk Based Inspection Based Resource Document, API Publication 581. The concept and theory of the methodology has been discussed in Chapter 3 of this report. The frameworks of both RBI qualitative and semi-quantitative risk analysis of RBI tool prototype are presented in this chapter.

Figure 3.5.1a to Figure 3.5.1g are frameworks for RBI Qualitative Level Analysis while Figure 3.5.2a to Figure 3.5.2k are frameworks for RBI Semi-Quantitative Level Analysis. Figure 3.5.2f(b) to Figure 3.5.2f(i) are the embedded frameworks for TMSF determination for likelihood analysis in RBI semi-quantitative analysis.

3.5.1 RBI Qualitative Risk Analysis Framework

To define the equipment factor: Size of study will affect the probability of failure of a component in the study.

EF1=15, full operating unit
EF2=5, a major section of an operating unit
EF3=0, a system or unit operation

Total of Equipment Factor

Damage factor: To measure risk associated with known damage mechanism

DF1=5, Active damage mechanisms that can cause corrosion cracking in carbon or low alloy steels
DF2=4, Potential catastrophic brittle failure including carbon steel materials due to low temperature operation or upset conditions, temper embrittlement, or materials not adequately qualified by impact testing
DF3=4, Mechanically thermally-induced fatigue failure has occurred and the fatigue mechanism might still be active
DF4=3, High temperature Hydrogen attack occuring
DF5=3, Corrosion cracking of austenitic stainless steels occurring as a result of the process
DF6=3, Localized corrosion is occurring
DF7=2, General corrosion is occurring
DF8=1, Creep damage is occurring in high temperature processes, including furnace and heaters
DF9=1, Materials degradation with such mechanisms as sigma phase formation, carburization, spheroidization, etc.
DF10=1, Other active damage mechanisms
DF11=10, Potential damage mechanisms in the operating unit have not been evaluated and are not being periodically reviewed by a qualifies materials engineer

Maximum DF is 20

Inspection Factor: To measure the effectiveness of the inspection program by identifying the active or anticipated damage

Vessel Inspection: To gage the effectiveness of vessel inspection program

IF1= -5, the inspection program is extensive and a variety of inspection methods and monitoring are being used
IF1= -2, formal inspection program is in place and some inspections are being done, but primarily visual and UT thickness readings
IF1= 0, no formal inspection program is in place

Piping Inspection: To gage the effectiveness of vessel inspection program

IF2= -5, the inspection program is extensive and a variety of inspection methods are being used
IF2= -2, formal inspection program is in place and some inspections are being done, but primarily visual and UT thickness readings
IF2= 0, no formal inspection program is in place

Overall Inspection Program: How comprehensive the inspection program design, and are the inspection results evaluated and used to modify the inspection program?

IF3= -5, deterioration mechanisms have been identified for each equipment item and the inspection program is modified based on the results of the program using a competent inspector or materials engineer
IF3= -2, inspection program design excludes either identification of failure mechanisms or does not include critical evaluation of all inspection results
IF3= 0, no criteria as stated before are met in the inspection program

Total IF value cannot exceed total DF value

Go to Figure 3.5.1b

Figure 3.5.1a

From Figure 3.5.1a

Condition Factor: To gage the effectiveness of plant maintenance and housekeeping efforts

In a plant walkthrough, how would the plant housekeeping be judged (including painting and insulation maintenance programs)?
CCF1 = 0, significantly better than industry standards
CCF1 =2, about industry standard
CCF1 = 5, significantly below industry standards

The quality of plant design and construction is:
CCF2= 0, significantly better than industry standards, where the owner has used more rigorous standards
CCF2=2, about industry standard, where typical contract standards were used
CCF2=5, significantly below industry standards

In a review of the effectiveness, fabrication, PM programs, and QA/QC would be judged in plant maintenance program:
CCF3=0, significantly better than industry standards
CCF3=2, about industry standard
CCF3=5, significantly below industry standards

Total of Condition Factor

Process Factor: To measure the potential of abnormal operations or upset conditions to result in initiating events that could lead to a loss of containement

The number of planned or unplanned process interruptions in an average year (for normal continuous process operations):

Number of operations	PF1
0 to 1	0
2 to 4	1
5 to 8	3
9 to 12	4
more than 12	5

Assess the potential for exceeding key process variables in the operation being evaluated:

PF2= 0, the process is extremely stable and no combination of upset conditions is known to exist that could cause runaway reaction or other unsafe conditions
PF2= 1, only very unusual circumstances could cause upset conditions to escalate into an unsafe conditions
PF2=5, possibility of loss of control is inherent in the process

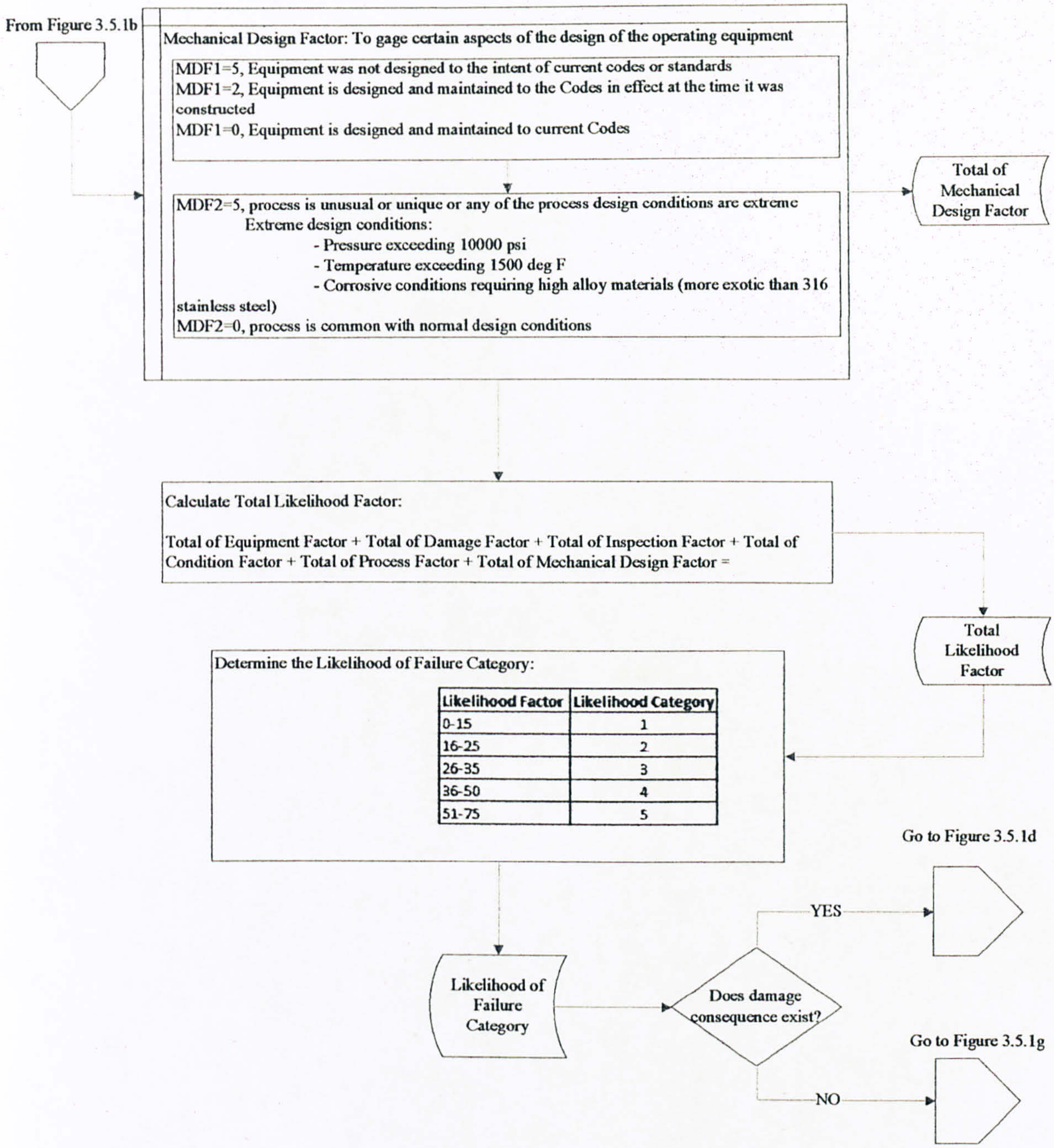
Assess the potential for protection devices, such as relief devices and critical sensing elements to be rendered inoperative as a result of plugging or fouling of the process fluid:

PF3=0, clean service, no plugging potential
PF3=1, slight fouling or plugging potential
PF3=3, significant fouling or plugging potential
PF3=5, protective devices have been found impaired in service

Total of Process Factor

Go to Figure 3.5.1c

Figure 3.5.1b



Likelihood Factor	Likelihood Category
0-15	1
16-25	2
26-35	3
36-50	4
51-75	5

Figure 3.5.1c

From Figure 3.5.1c

Chemical factor: To measure chemical's inherent tendency to ignite . Should be based on the predominate or representative material in the stream. Separate analysis should be performed if the unit has a number of different process streams.

Determine a "Flash Factor" using NFPA Flammable Hazard Rating (the Red diamond on the NFPA Hazard Identification System Sign) – Enter the NFPA Reactivity Hazard Rating

Determine a "Reactivity Factor" using the NFPA Reactivity Hazard Rating System (the Yellow diamond on the NFPA Hazard Identification System Sign) – Enter the NFPA Reactivity Hazard Rating

Reactivity Factor

Flash factor		1	2	3	4
	1	7	9	12	15
	2	10	12	15	20
	3	12	15	18	25
	4	13	15	20	25

Total of Chemical Factor

Quantity Factor: To determine possible largest amount of material which could be released from a unit in a single scenario

For amount material released, use the largest amount of flammable inventory that can be lost in a single leak event:

Material Released	Quantity Factor
<1000 pounds	15
1K-2K pounds	20
2K-10K pounds	25
10K-30K pounds	28
30K-80K pounds	31
80K-200K pounds	34
200K-700K pounds	37
700K-1million pounds	39
1-2million pounds	41
2-10million pounds	45
>10million pounds	50

Total of Quantity Factor

State Factor: To indicate the fluid's tendency to vaporize and disperse when released into the environment

Select state factor based on the normal (atmospheric pressure) boiling temperature in deg F:

Boiling Point (deg F)	State Factor
below -100	8
*-100 to 100	6
100 to 250	5
250 to 400	1
above 400	-3

Total of State Factor

Autoignition Factor: Penalty applied to fluid that is processed at a temperature above its autoignition temperature

AF= -10, for processed fluid below its AIT

AF are listed as below in the table, for processed fluid above its AIT (it is based on the normal boiling point of the fluid:

Boiling point (deg F)	Autoignition Factor
below 10	3
0 to 300	7
above 300	13

Total of Autoignition Factor

Go to Figure 3.5.1e

Figure 3.5.1d

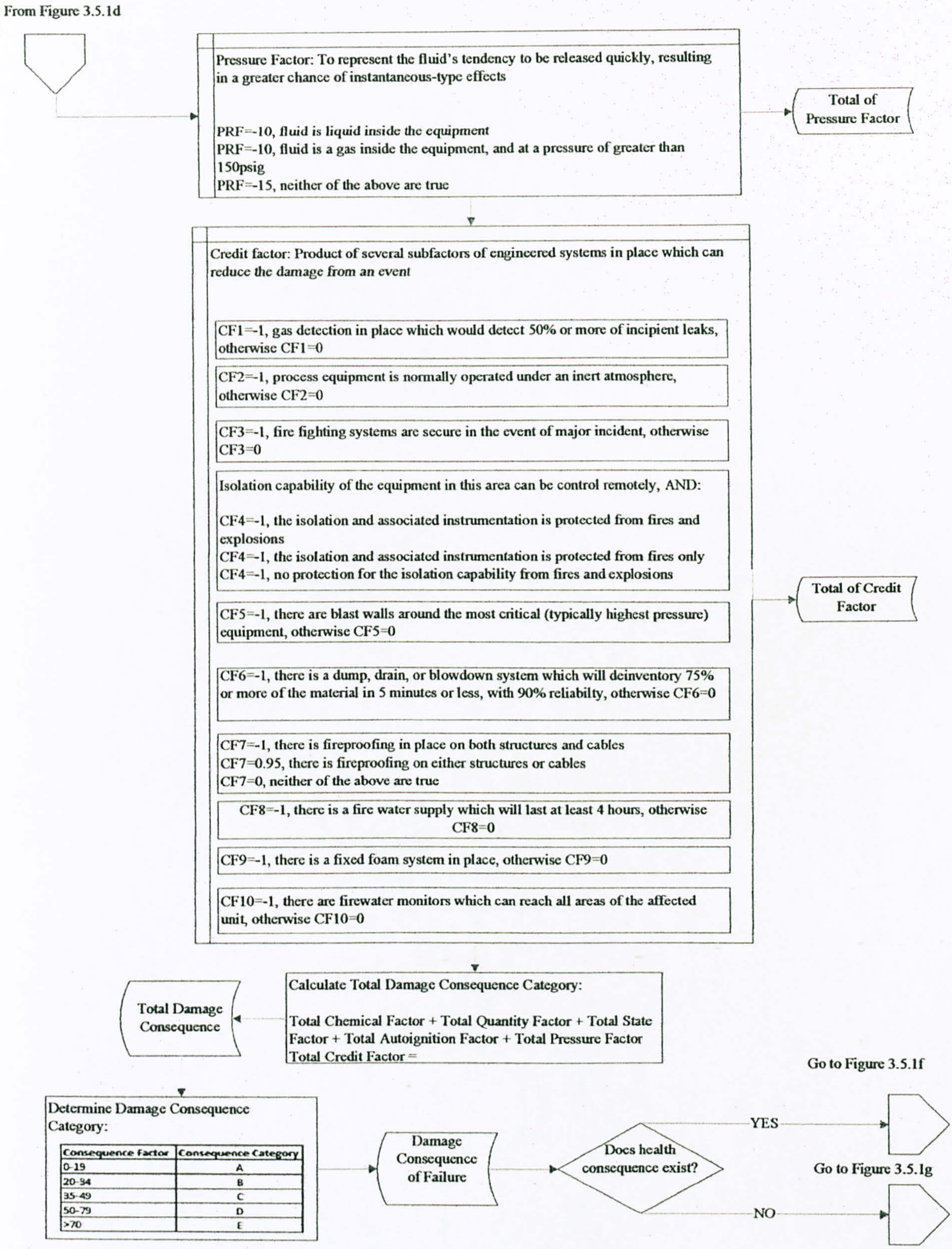

From Figure 3.5.1d
Pressure Factor: To represent the fluid's tendency to be released quickly, resulting in a greater chance of instantaneous-type effects
PRF=-10, fluid is liquid inside the equipment
PRF=-10, fluid is a gas inside the equipment, and at a pressure of greater than 150psig
PRF=-15, neither of the above are true
Total of Pressure Factor
Credit factor: Product of several subfactors of engineered systems in place which can reduce the damage from an event
CF1=-1, gas detection in place which would detect 50% or more of incipient leaks, otherwise CF1=0
CF2=-1, process equipment is normally operated under an inert atmosphere, otherwise CF2=0
CF3=-1, fire fighting systems are secure in the event of major incident, otherwise CF3=0
Isolation capability of the equipment in this area can be control remotely, AND:
CF4=-1, the isolation and associated instrumentation is protected from fires and explosions
CF4=-1, the isolation and associated instrumentation is protected from fires only
CF4=-1, no protection for the isolation capability from fires and explosions
CF5=-1, there are blast walls around the most critical (typically highest pressure) equipment, otherwise CF5=0
CF6=-1, there is a dump, drain, or blowdown system which will deinventory 75% or more of the material in 5 minutes or less, with 90% reliabilty, otherwise CF6=0
CF7=-1, there is fireproofing in place on both structures and cables
CF7=0.95, there is fireproofing on either structures or cables
CF7=0, neither of the above are true
CF8=-1, there is a fire water supply which will last at least 4 hours, otherwise CF8=0
CF9=-1, there is a fixed foam system in place, otherwise CF9=0
CF10=-1, there are firewater monitors which can reach all areas of the affected unit, otherwise CF10=0
Total of Credit Factor
Calculate Total Damage Consequence Category:
Total Chemical Factor + Total Quantity Factor + Total State Factor + Total Autoignition Factor + Total Pressure Factor Total Credit Factor =
Total Damage Consequence
Determine Damage Consequence Category:
Consequence Factor | Consequence Category
0-19 | A
20-34 | B
35-49 | C
50-79 | D
>70 | E
Damage Consequence of Failure
Does health consequence exist?
YES
NO
Go to Figure 3.5.1f
Go to Figure 3.5.1g

Figure 3.5.1e

From Figure 3.5.1e

Toxic Quantity: To measure of both the quantity of the chemical and its toxicity

STEP1: TQF1

For amount of chemical released, use the largest amount of toxic inventory that can be lost in a single leak event

Material Released	Quantity Factor
<1000 pounds	15
1K-10K pounds	20
10K-100K pounds	27
>1 million pounds	35

STEP2: TQF2

To estimate the toxicity factor from below table based on blue diamond in the NFPA Hazard Identification System:

NFPA	Toxicity Factor
1	-20
2	-10
3	0
4	20

Total of quantity factor

Dispersibility Factor: To measure the ability of the material to disperse, at typical process conditions

DIF is determined from below table:

Boiling Point (deg F)	Dispersibility Factor
<30	1
30-80	0.5
80-140	0.3
140-200	0.1
200-300	0.05
>300	0.03

Total of Dispersibilty factor

Credit Factor: Accounts for safety features that reduce the consequences of a toxic release by detection, isolation, and mitigation

CRF1=-1, there are detectors in place for the process fluid of interest that would detect 50% or more of incipient leaks, otherwise CRF1=0

CRF2=-1, major vessels containing this material can be isolated automatically, and isolation is initiated from a high reading from a toxic material detector
CRF2=-5, isolation is remote with a manual initiation
CRF2=-25, isolation is manually operated only
CRF2=0, neither of the above are true

CRF3=-5, there is a system in place that has proven to be effective in mitigating at least 90% of the fluid, otherwise CRF3=1

Total of Credit Factor

Population Factor: To measure the potential number of people that can be affected by the toxic event

Estimate population factor from below table. This is based on the number of people, on the average, within one-quarter mile of the release point. Consider both onsite and offsite populations. Within the plant boundaries, use daytime population counts:

Number of people within 1/4 mile radius	Population Factor
<10	0
10-100	7
100-1000	15
1000-10000	20

Total Population Factor

Calculate Total Health Consequence Category:

Total Quantity Factor + Total Dispersibility Factor + Total Credit Factor + Total Population Factor =

Total Health Consequence Category:

Health Consequence	Health Consequence Category
<10	A
10 to 19	B
20-29	C
30-39	D
>40	E

Category?

Health Consequence Category

Go to Figure 3.5.1g

Figure 3.5.1f

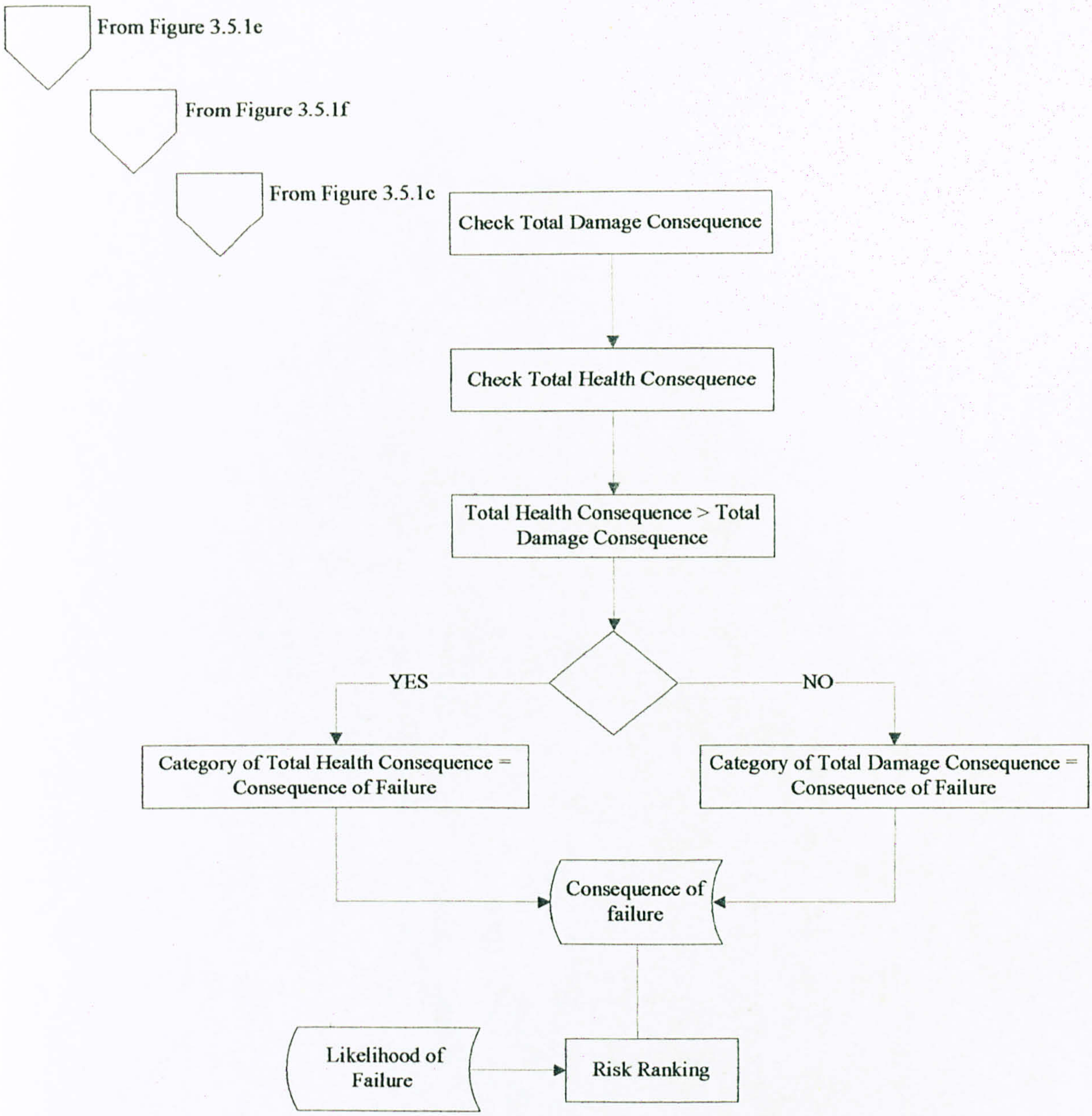

From Figure 3.5.1e
From Figure 3.5.1f
From Figure 3.5.1c
Check Total Damage Consequence
Check Total Health Consequence
Total Health Consequence > Total Damage Consequence
YES
NO
Category of Total Health Consequence = Consequence of Failure
Category of Total Damage Consequence = Consequence of Failure
Consequence of failure
Likelihood of Failure
Risk Ranking

Figure 3.5.1g

3.5.2 RBI Semi-Quantitative Risk Analysis Framework

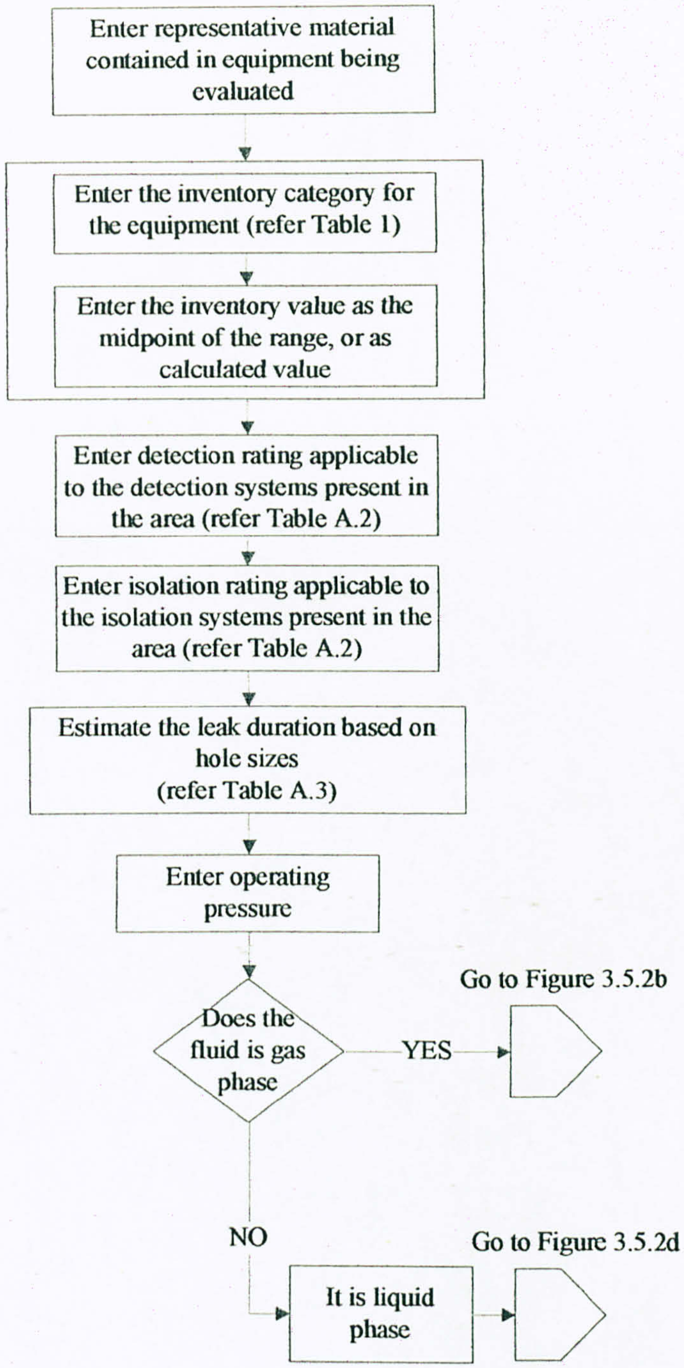


Figure 3.5.2a

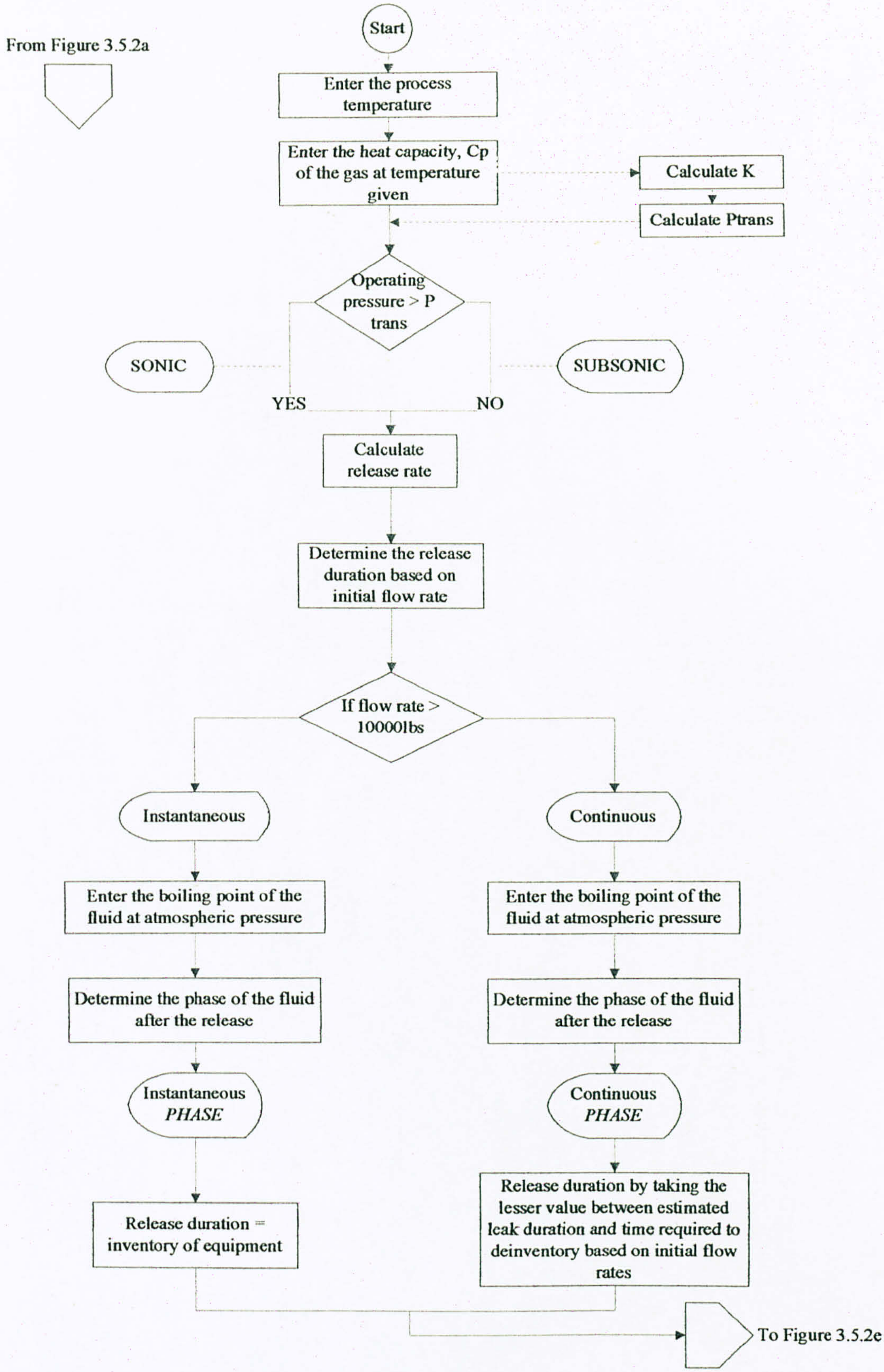

From Figure 3.5.2a
Start
Enter the process temperature
Enter the heat capacity, Cp of the gas at temperature given
Calculate K
Calculate Ptrans
Operating pressure > P trans
SONIC
SUBSONIC
YES
NO
Calculate release rate
Determine the release duration based on initial flow rate
If flow rate > 10000lbs
Instantaneous
Continuous
Enter the boiling point of the fluid at atmospheric pressure
Enter the boiling point of the fluid at atmospheric pressure
Determine the phase of the fluid after the release
Determine the phase of the fluid after the release
Instantaneous PHASE
Continuous PHASE
Release duration = inventory of equipment
Release duration by taking the lesser value between estimated leak duration and time required to deinventory based on initial flow rates
To Figure 3.5.2e

Figure 3.5.2b

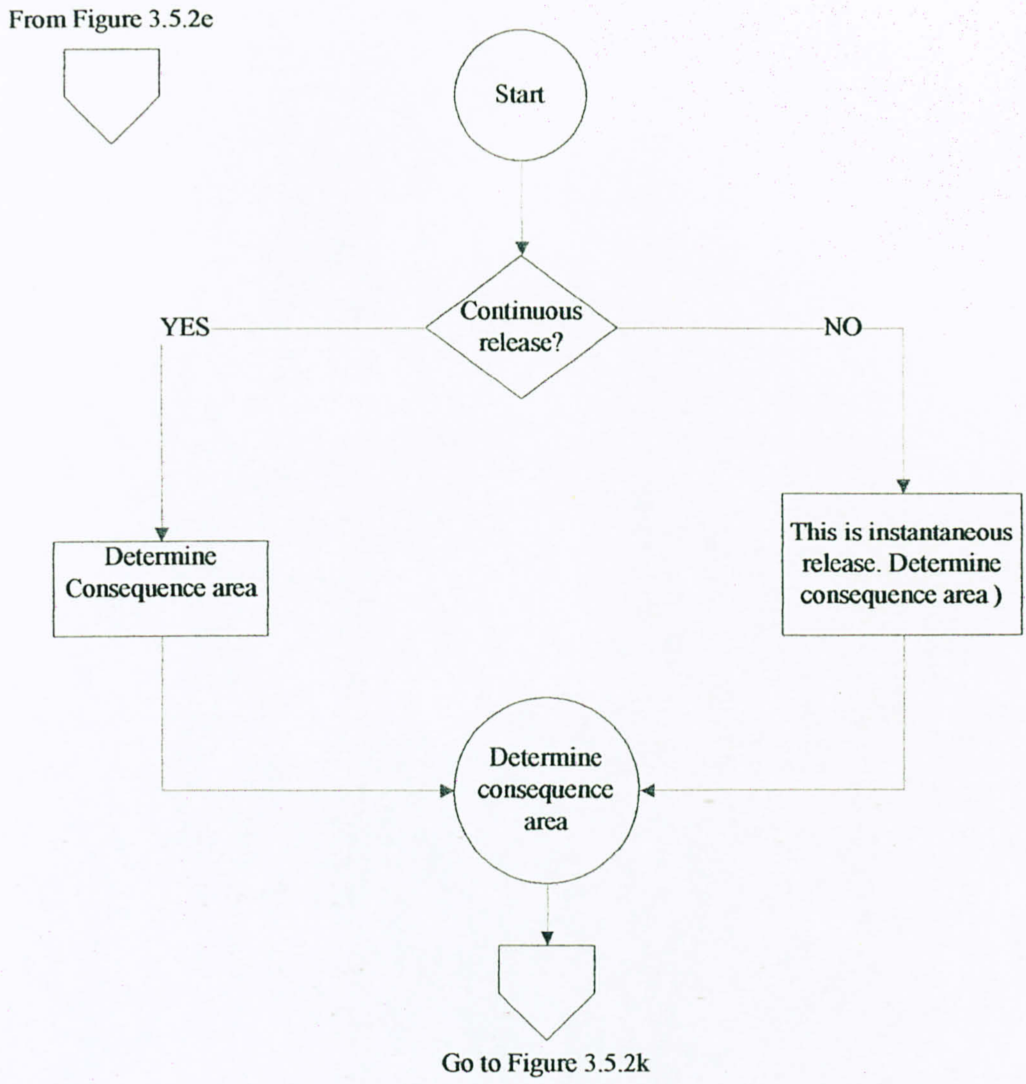

From Figure 3.5.2e
Start
Continuous release?
YES
NO
Determine Consequence area
This is instantaneous release. Determine consequence area)
Determine consequence area
Go to Figure 3.5.2k

Figure 3.5.2c

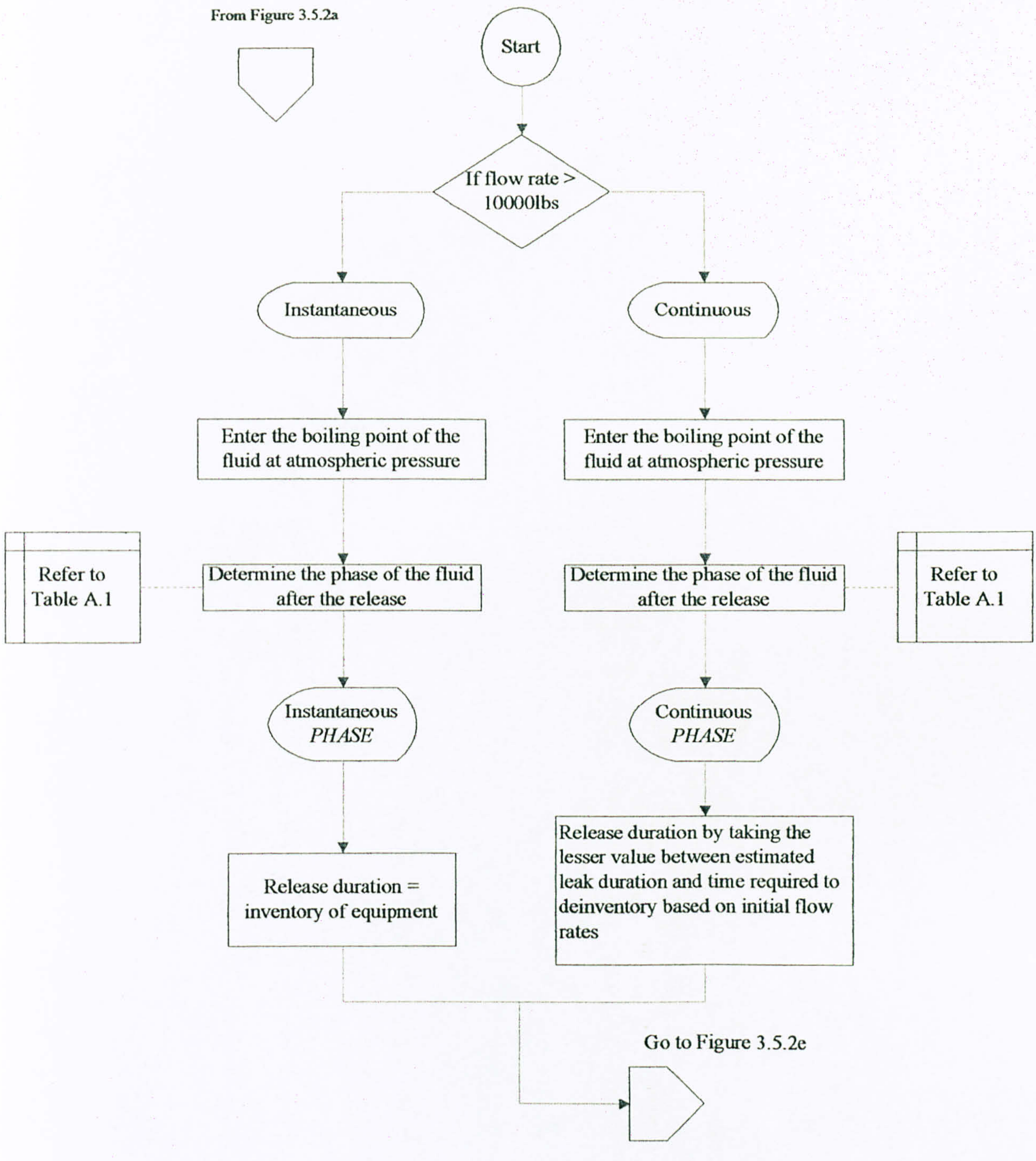

From Figure 3.5.2a
Start
If flow rate > 10000lbs
Instantaneous
Continuous
Enter the boiling point of the fluid at atmospheric pressure
Enter the boiling point of the fluid at atmospheric pressure
Refer to Table A.1
Determine the phase of the fluid after the release
Determine the phase of the fluid after the release
Refer to Table A.1
Instantaneous PHASE
Continuous PHASE
Release duration = inventory of equipment
Release duration by taking the lesser value between estimated leak duration and time required to deinventory based on initial flow rates
Go to Figure 3.5.2e

Figure 3.5.2d

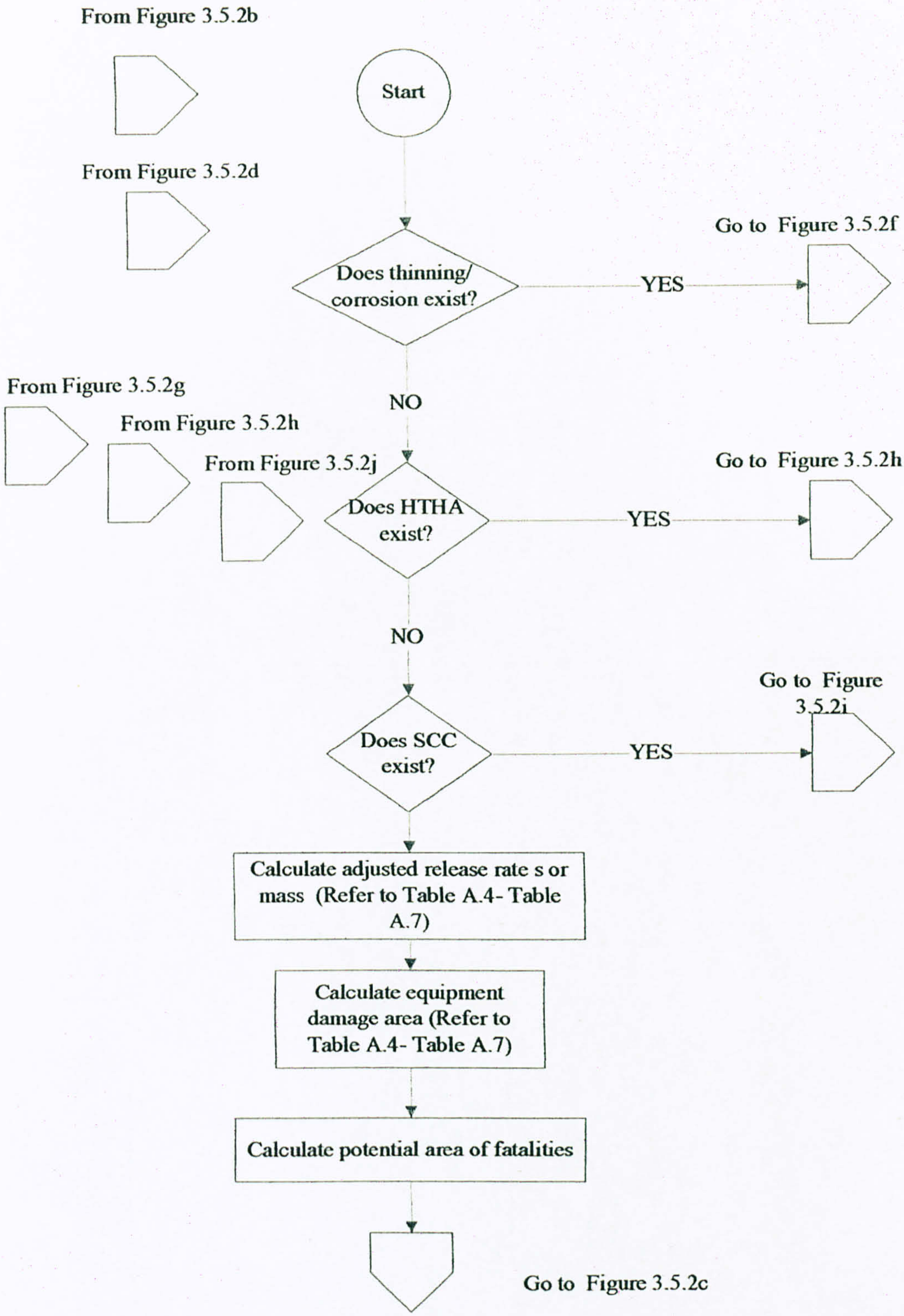

From Figure 3.5.2b
Start
From Figure 3.5.2d
Go to Figure 3.5.2f
Does thinning/ corrosion exist?
YES
From Figure 3.5.2g
NO
From Figure 3.5.2h
From Figure 3.5.2j
Go to Figure 3.5.2h
Does HTHA exist?
YES
NO
Go to Figure 3.5.2i
Does SCC exist?
YES
Calculate adjusted release rate s or mass (Refer to Table A.4- Table A.7)
Calculate equipment damage area (Refer to Table A.4- Table A.7)
Calculate potential area of fatalities
Go to Figure 3.5.2c

Figure 3.5.2e

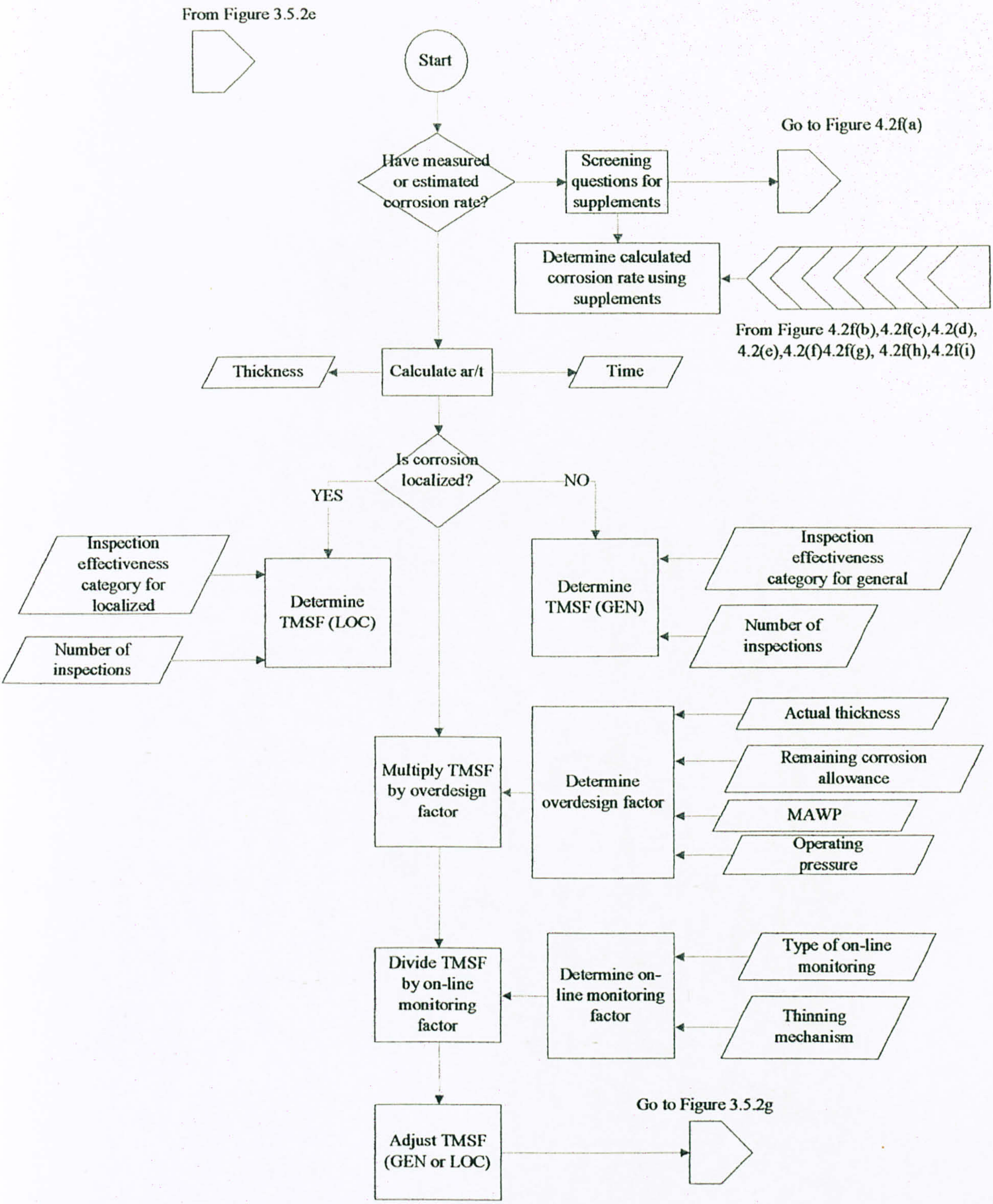

From Figure 3.5.2e
Start
Have measured or estimated corrosion rate?
Screening questions for supplements
Go to Figure 4.2f(a)
Determine calculated corrosion rate using supplements
From Figure 4.2f(b),4.2f(c),4.2(d), 4.2(e),4.2(f)4.2f(g), 4.2f(h),4.2f(i)
Thickness
Calculate ar/t
Time
Is corrosion localized?
YES
NO
Inspection effectiveness category for localized
Number of inspections
Determine TMSF (LOC)
Determine TMSF (GEN)
Inspection effectiveness category for general
Number of inspections
Actual thickness
Remaining corrosion allowance
MAWP
Operating pressure
Multiply TMSF by overdesign factor
Determine overdesign factor
Divide TMSF by on-line monitoring factor
Determine on-line monitoring factor
Type of on-line monitoring
Thinning mechanism
Adjust TMSF (GEN or LOC)
Go to Figure 3.5.2g

Figure 3.5.2f

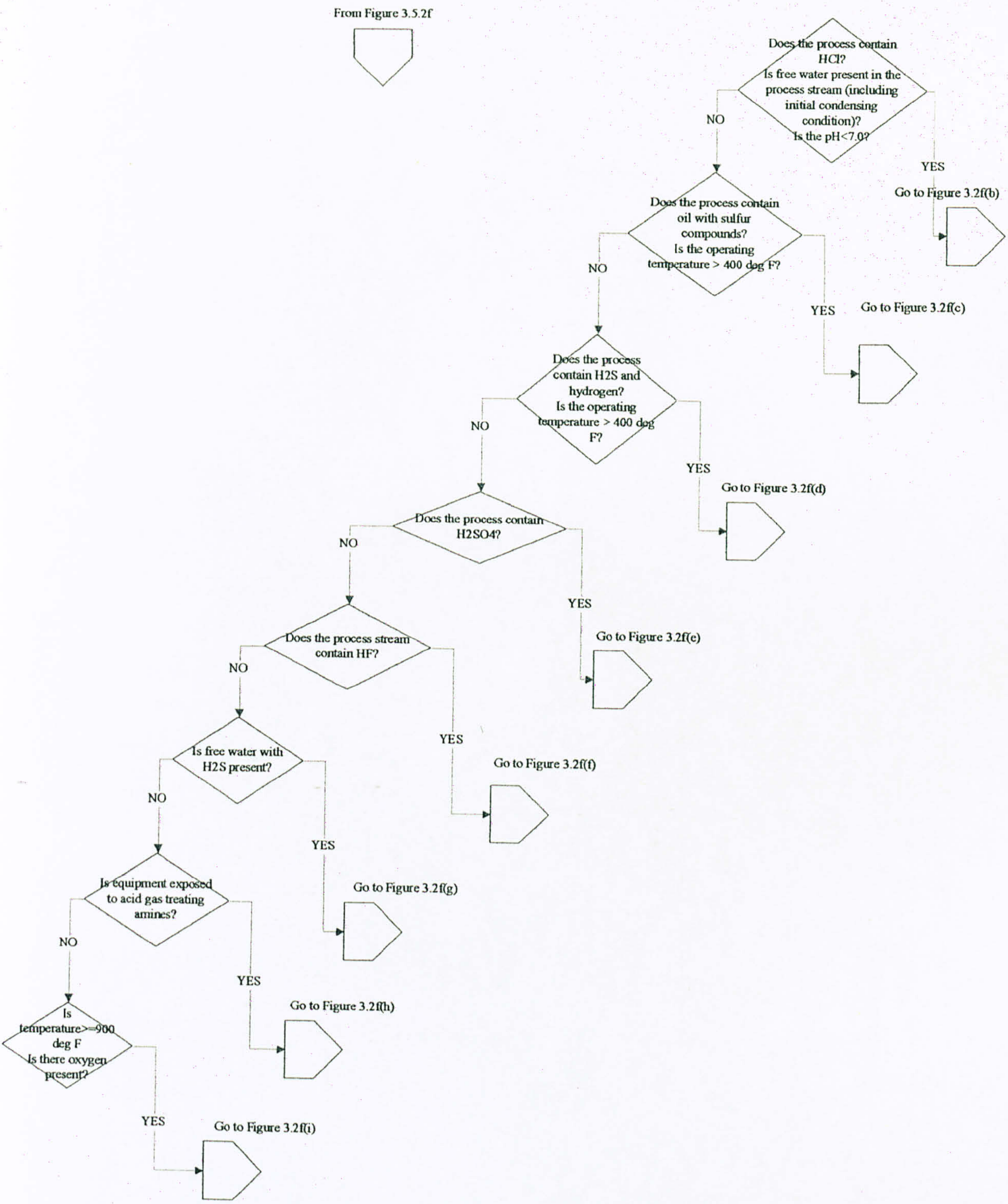


Figure 3.5.2f (a)

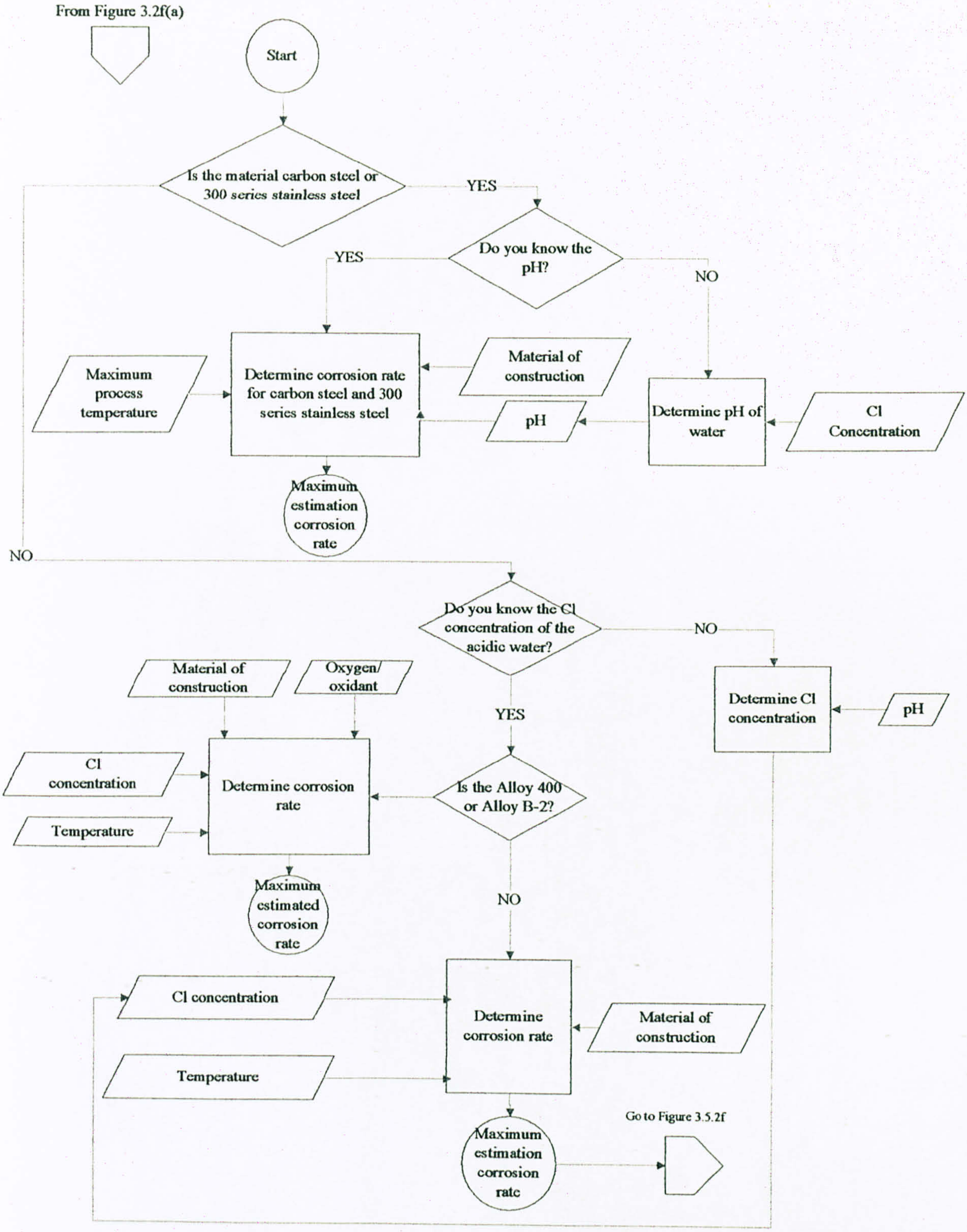


Figure 3.5.2f (b)

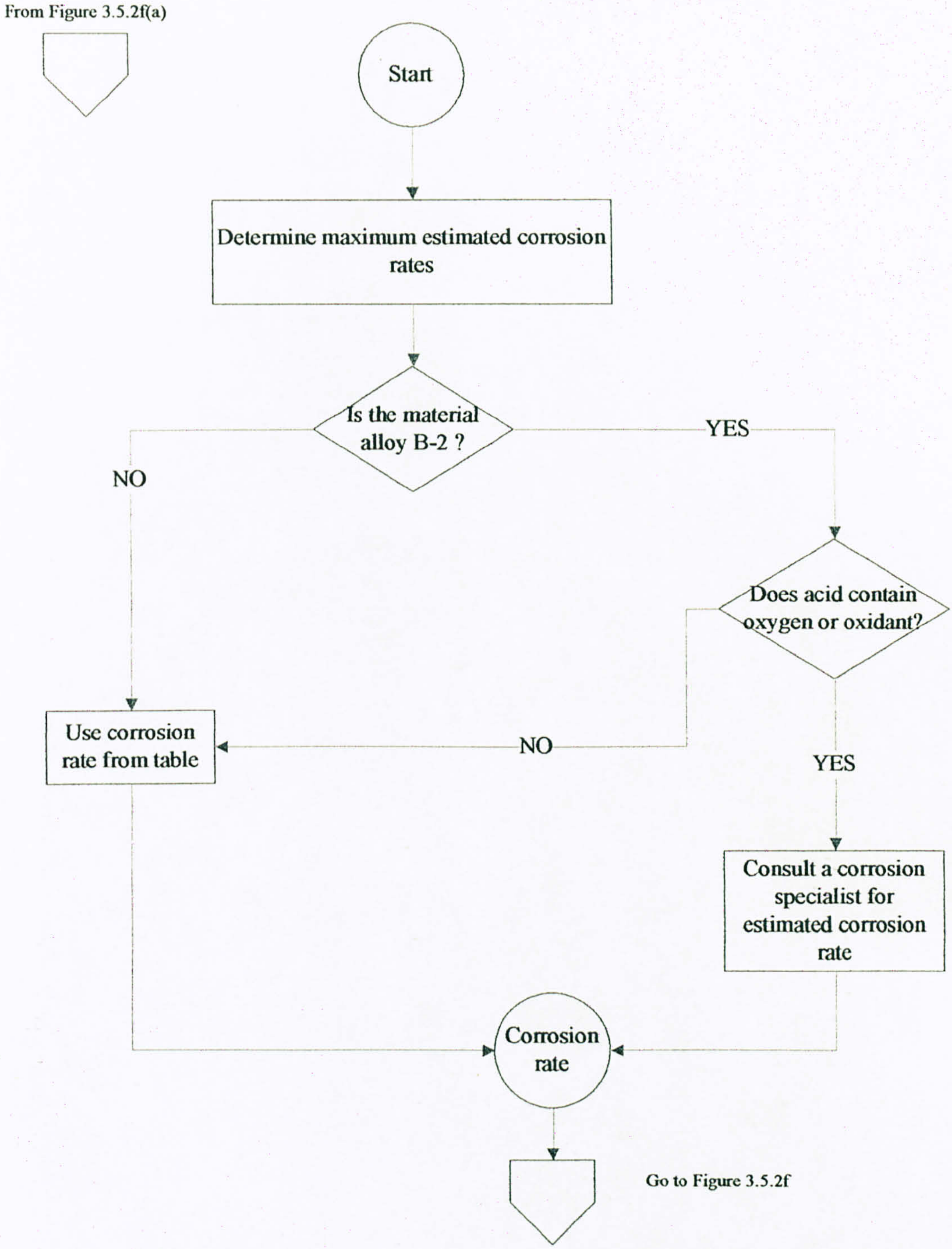


Figure 3.5.2f (c)

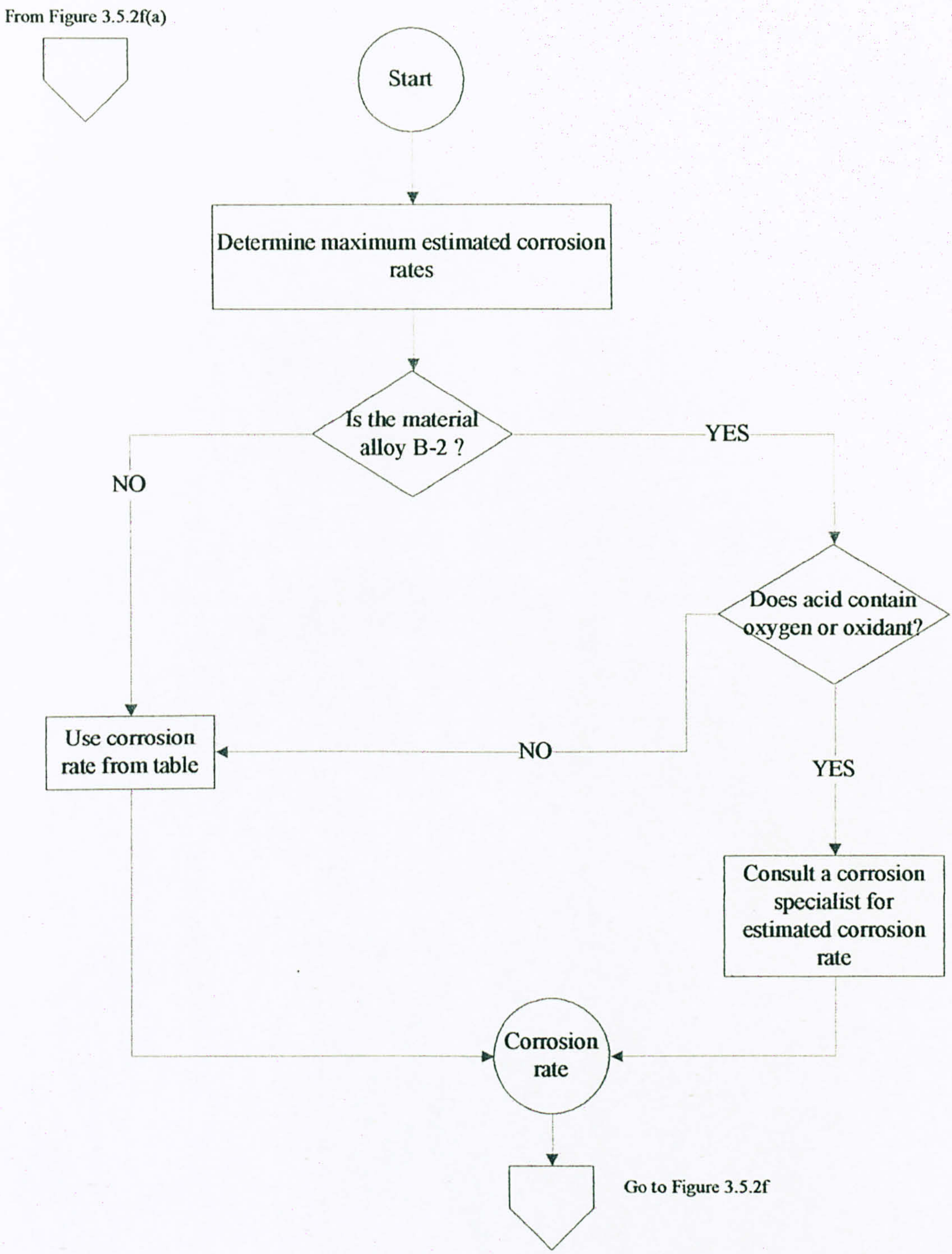


Figure 3.5.2f (d)

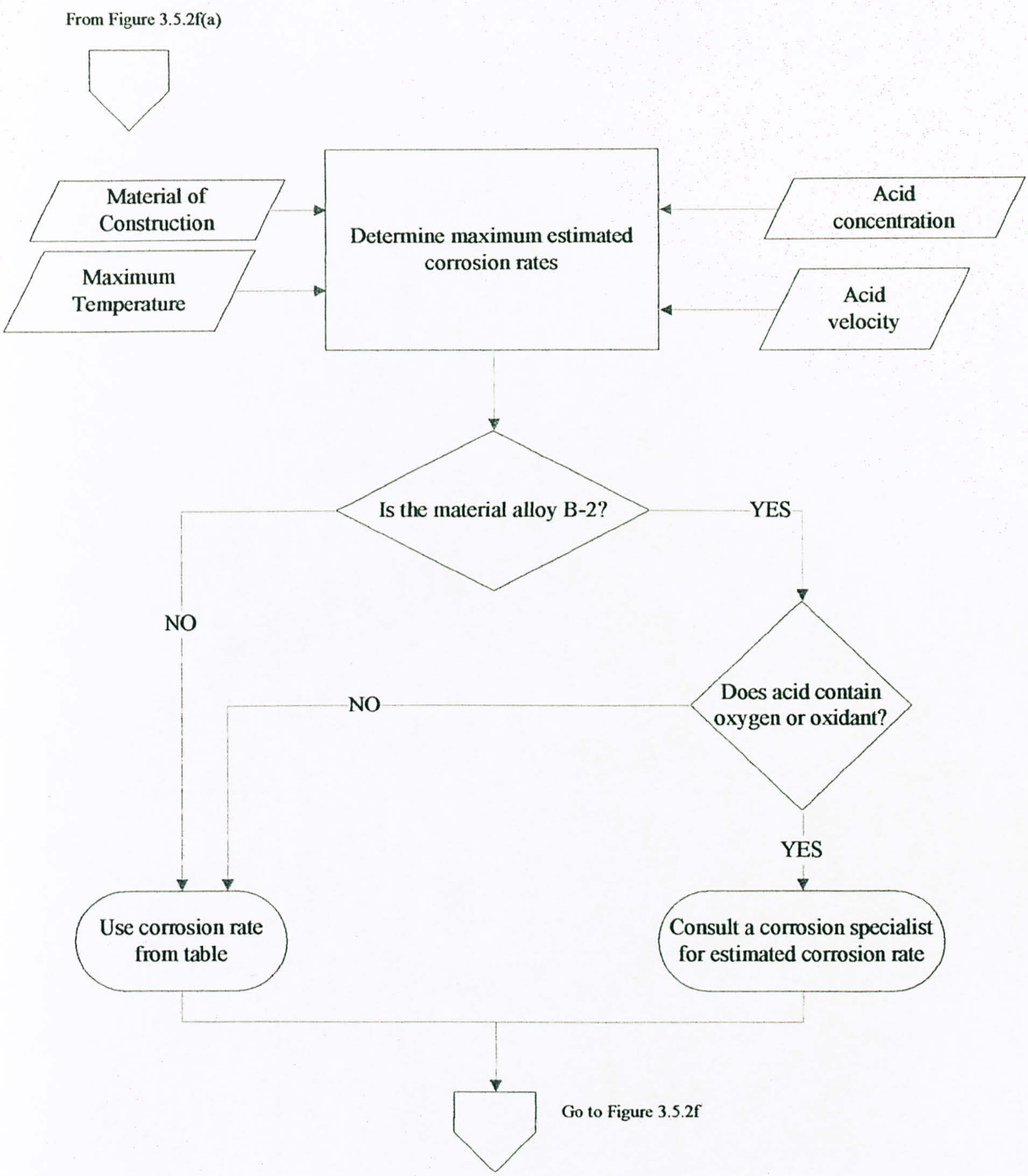


Figure 3.5.2f (e)

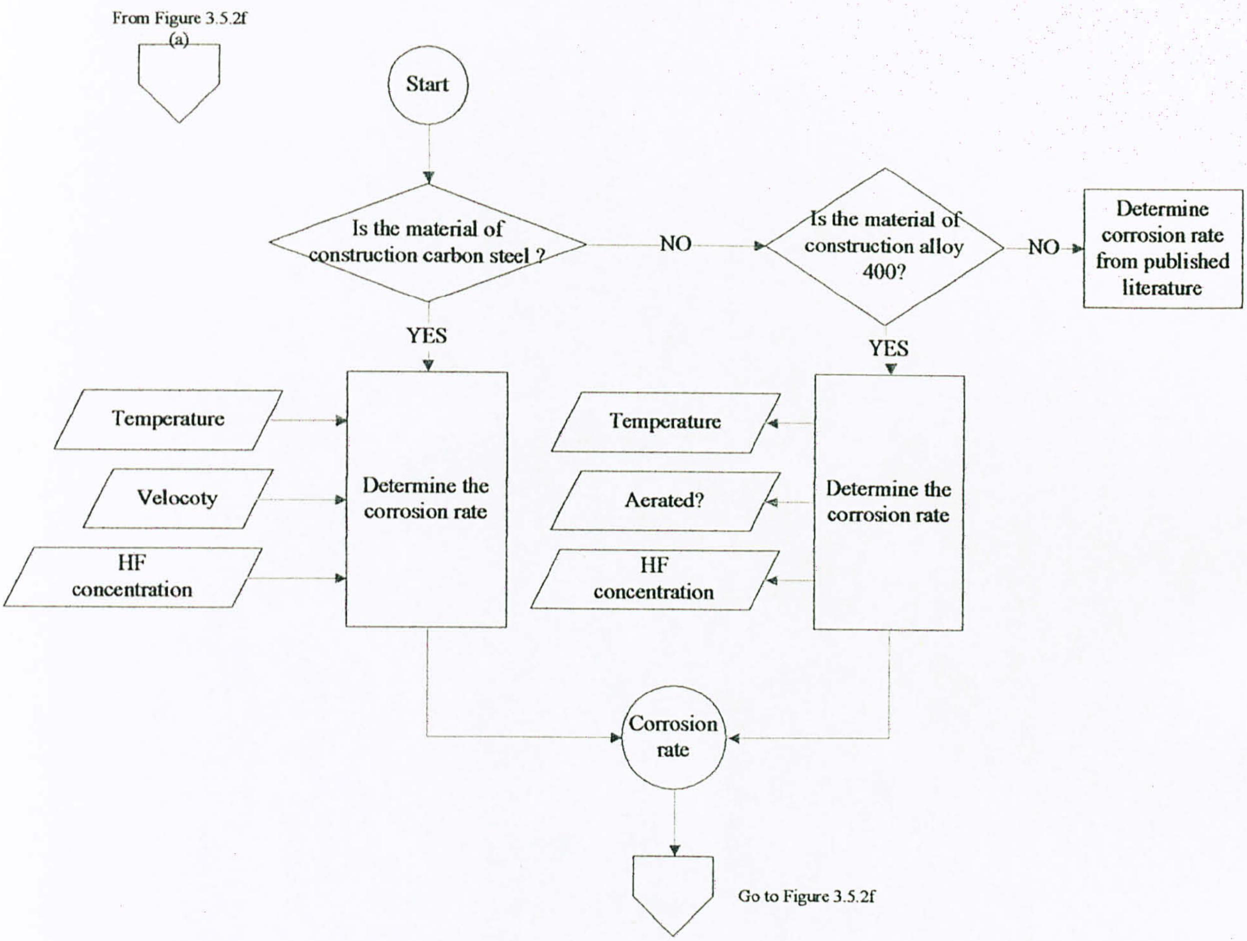


Figure 3.5.2f (f)

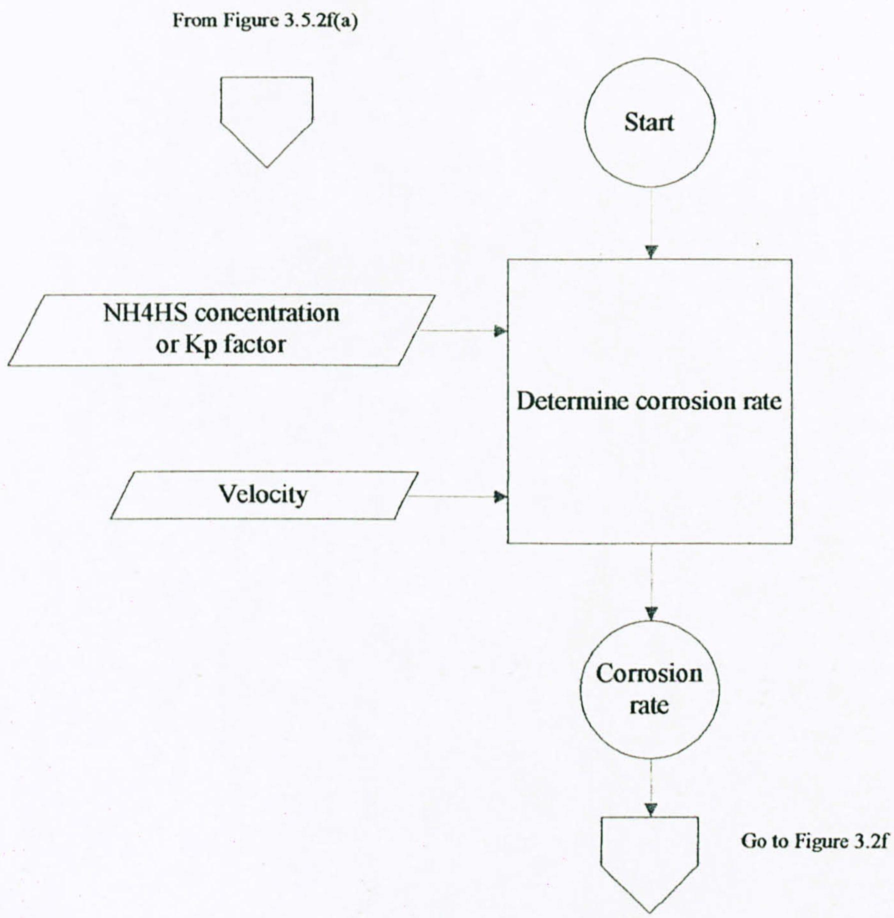


Figure 3.5.2f (g)

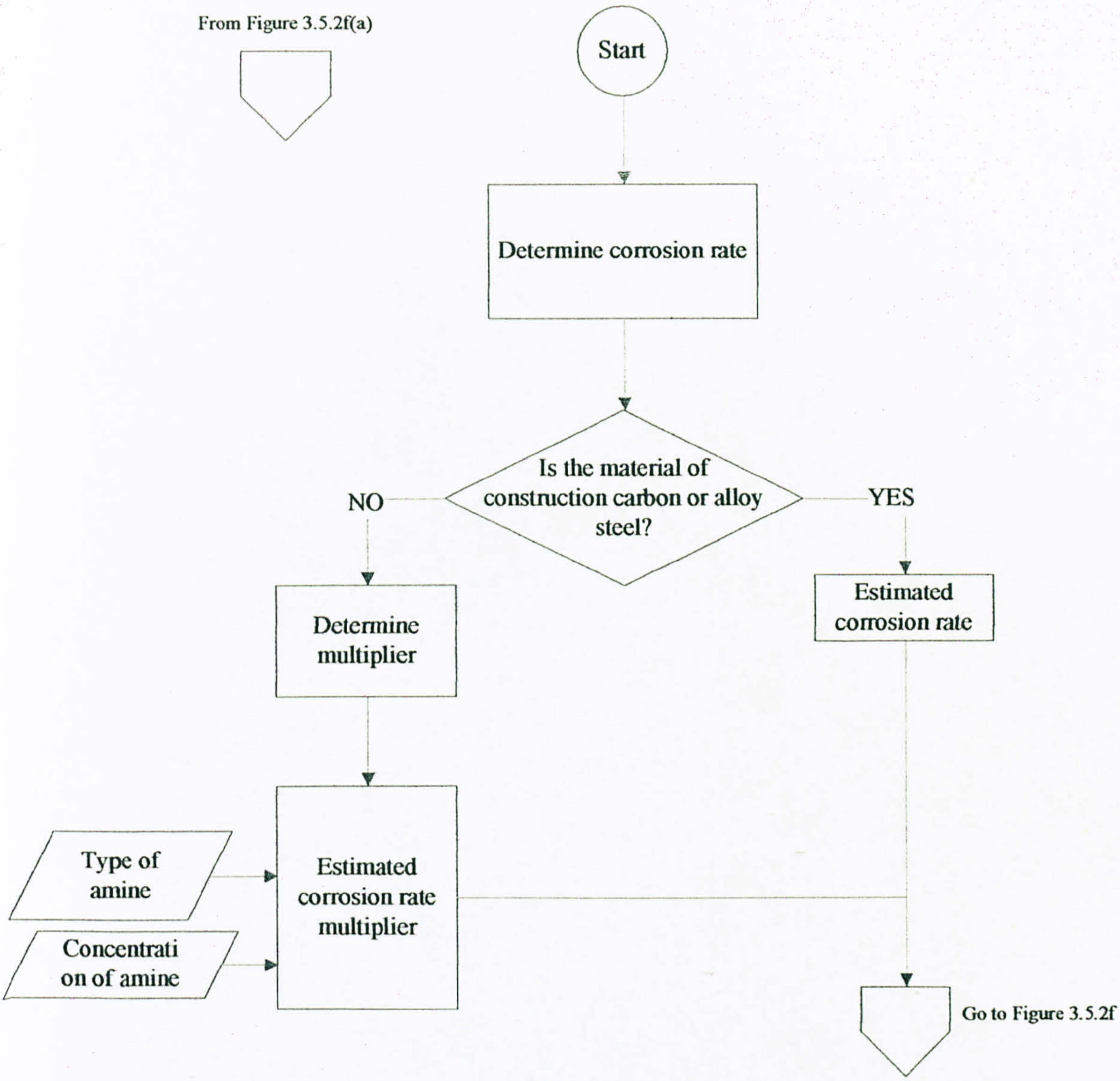


Figure 3.5.2f (h)

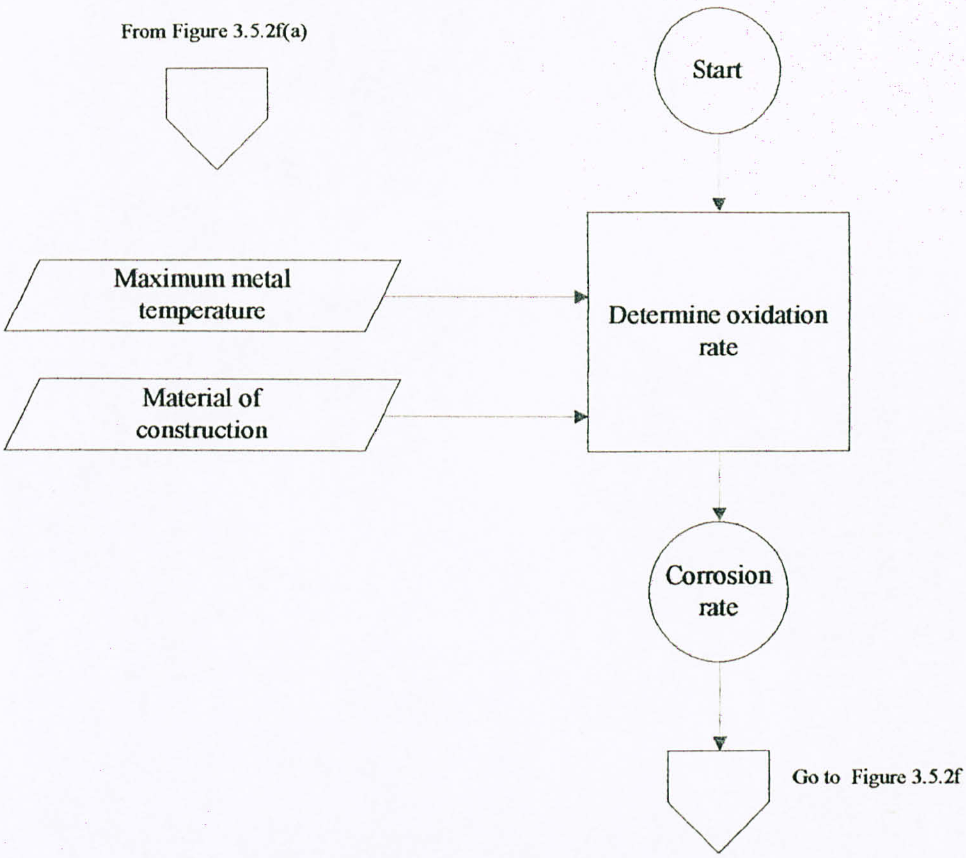


Figure 3.5.2f (i)

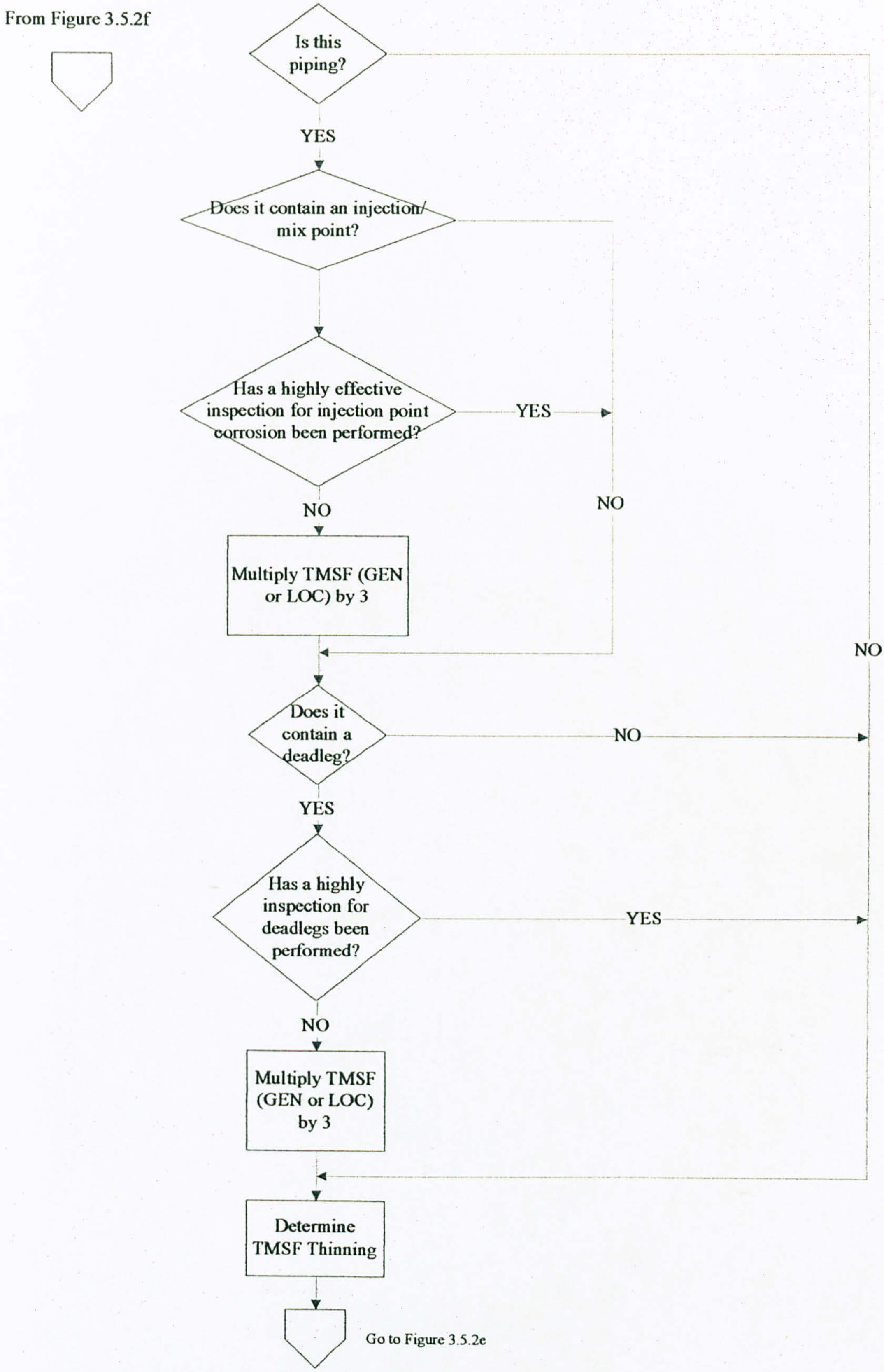

From Figure 3.5.2f
Is this piping?
YES
Does it contain an injection/ mix point?
Has a highly effective inspection for injection point corrosion been performed?
YES
NO
NO
Multiply TMSF (GEN or LOC) by 3
NO
Does it contain a deadleg?
NO
YES
Has a highly inspection for deadlegs been performed?
YES
NO
Multiply TMSF (GEN or LOC) by 3
Determine TMSF Thinning
Go to Figure 3.5.2e

Figure 3.5.2g

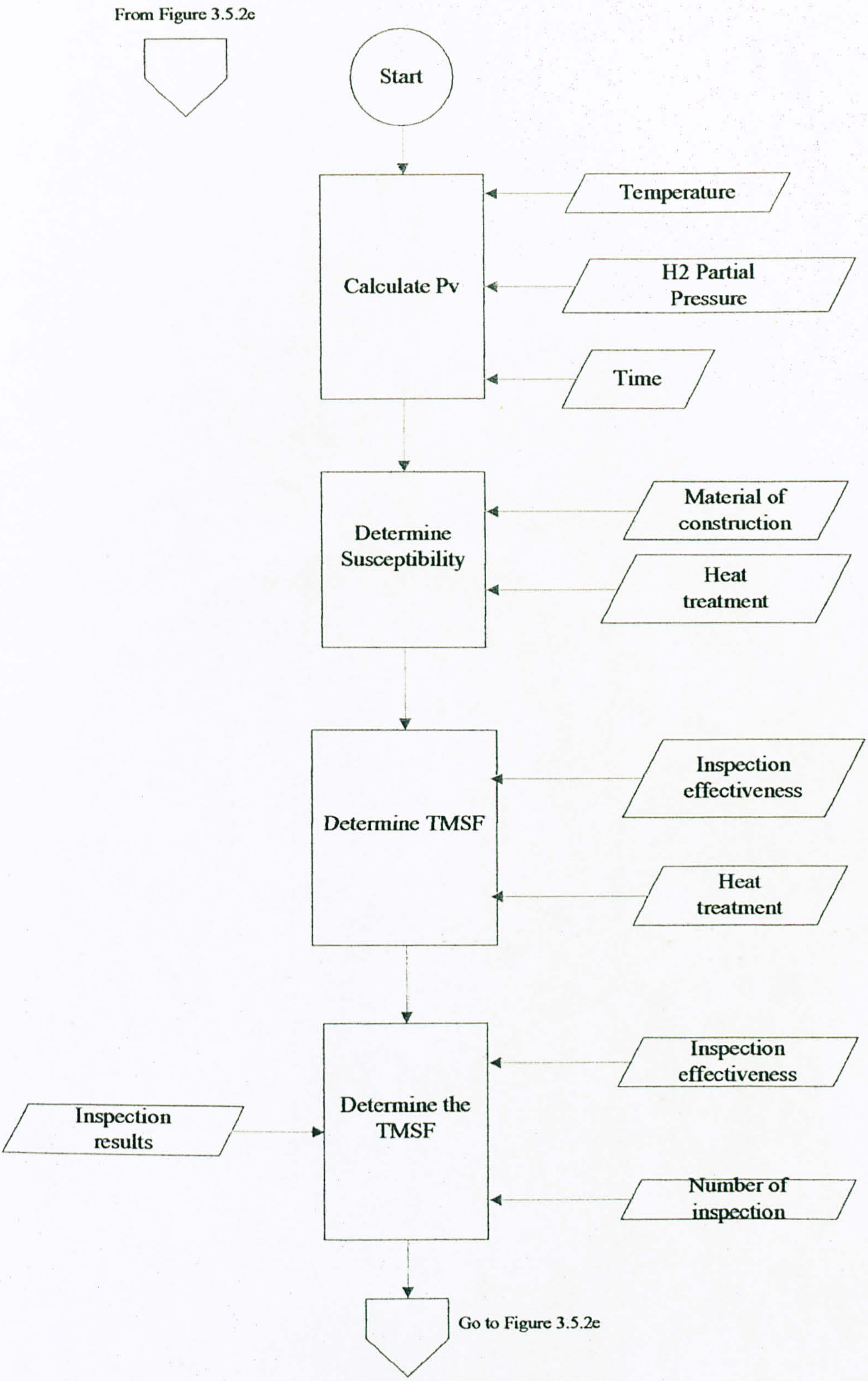

From Figure 3.5.2e
Start
Calculate Pv
Temperature
H2 Partial Pressure
Time
Determine Susceptibility
Material of construction
Heat treatment
Determine TMSF
Inspection effectiveness
Heat treatment
Determine the TMSF
Inspection effectiveness
Inspection results
Number of inspection
Go to Figure 3.5.2e

Figure 3.5.2h

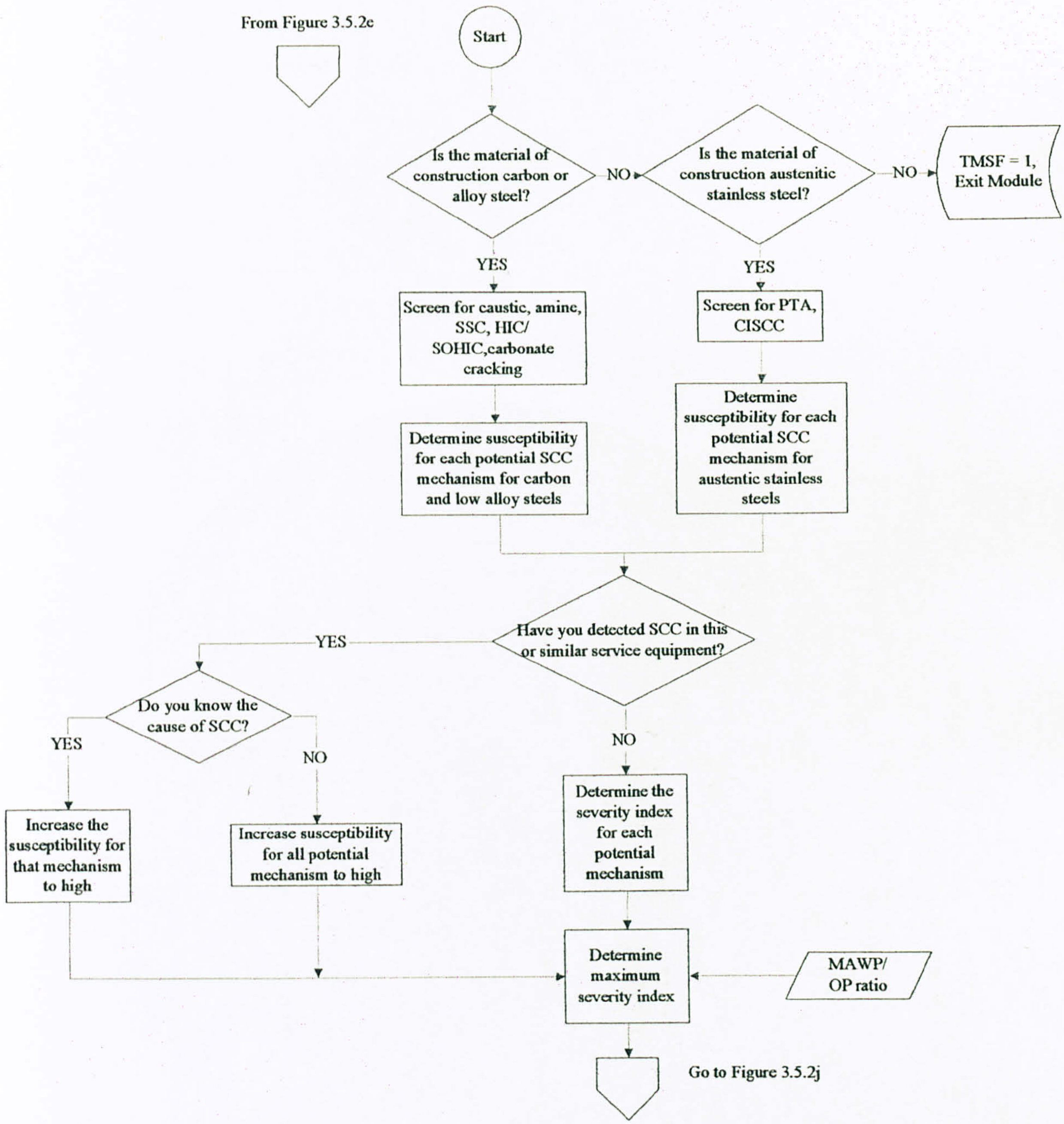

From Figure 3.5.2e
Start
Is the material of construction carbon or alloy steel?
NO
Is the material of construction austenitic stainless steel?
NO
TMSF = 1, Exit Module
YES
YES
Screen for caustic, amine, SSC, HIC/ SOHIC,carbonate cracking
Screen for PTA, CISCC
Determine susceptibility for each potential SCC mechanism for carbon and low alloy steels
Determine susceptibility for each potential SCC mechanism for austentic stainless steels
Have you detected SCC in this or similar service equipment?
YES
Do you know the cause of SCC?
YES
NO
NO
Increase the susceptibility for that mechanism to high
Increase susceptibility for all potential mechanism to high
Determine the severity index for each potential mechanism
Determine maximum severity index
MAWP/ OP ratio
Go to Figure 3.5.2j

Figure 3.5.2i

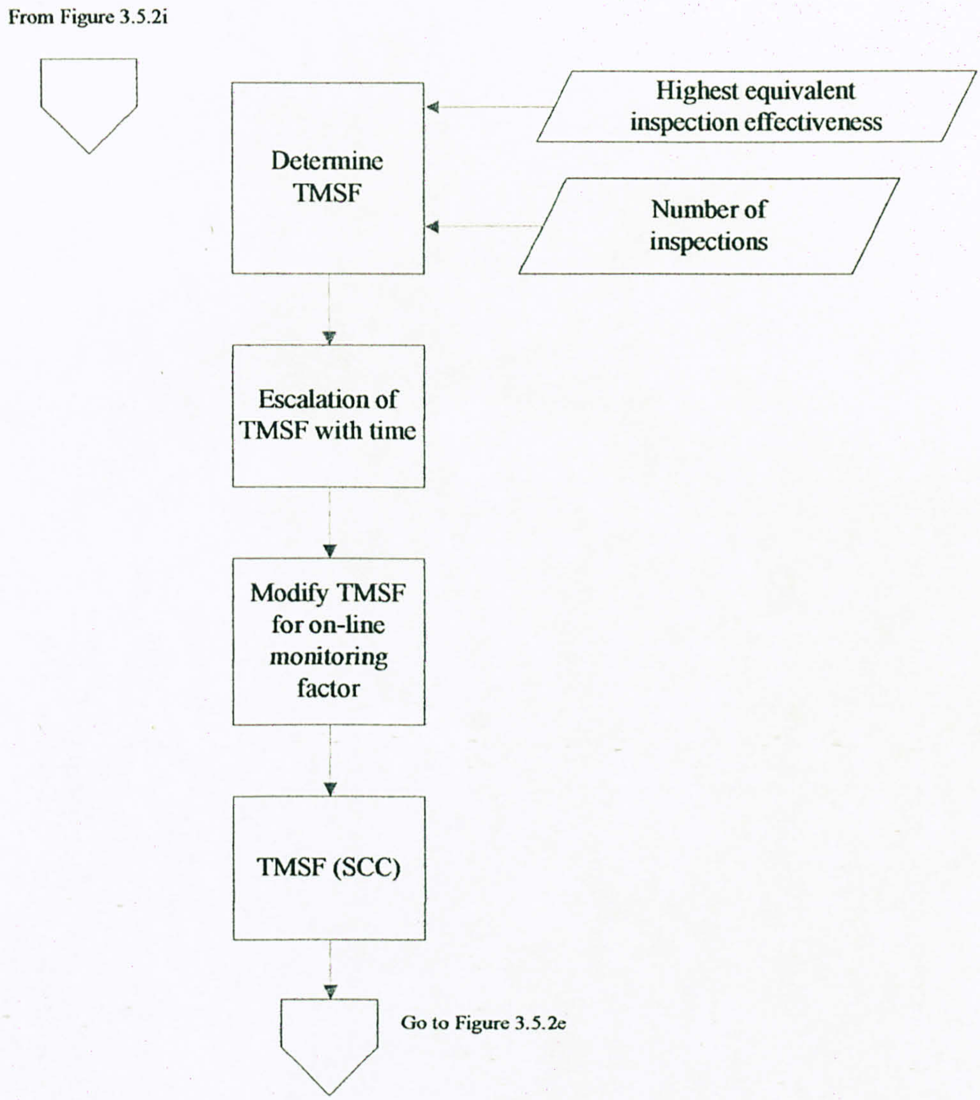

From Figure 3.5.2i
Determine
TMSF
Highest equivalent
inspection effectiveness
Number of
inspections
Escalation of
TMSF with time
Modify TMSF
for on-line
monitoring
factor
TMSF (SCC)
Go to Figure 3.5.2e

Figure 3.5.2j

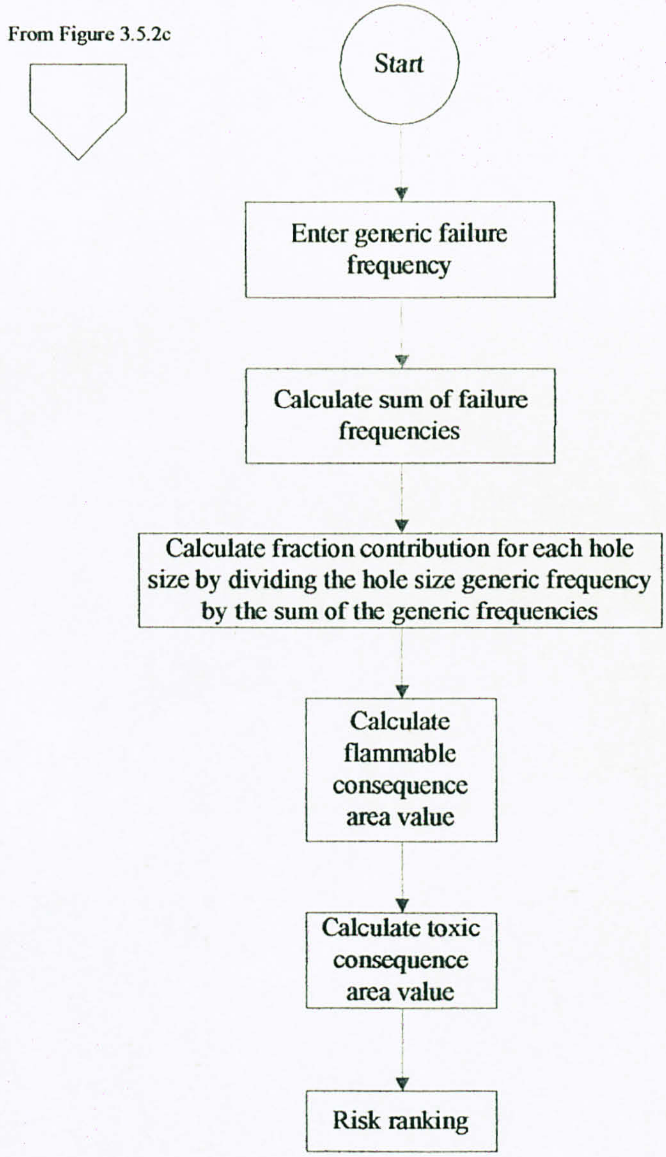

From Figure 3.5.2c
Start
Enter generic failure frequency
Calculate sum of failure frequencies
Calculate fraction contribution for each hole size by dividing the hole size generic frequency by the sum of the generic frequencies
Calculate flammable consequence area value
Calculate toxic consequence area value
Risk ranking

Figure 3.5.2k

3.6 RBI Tool Development by Using Visual Basic Application

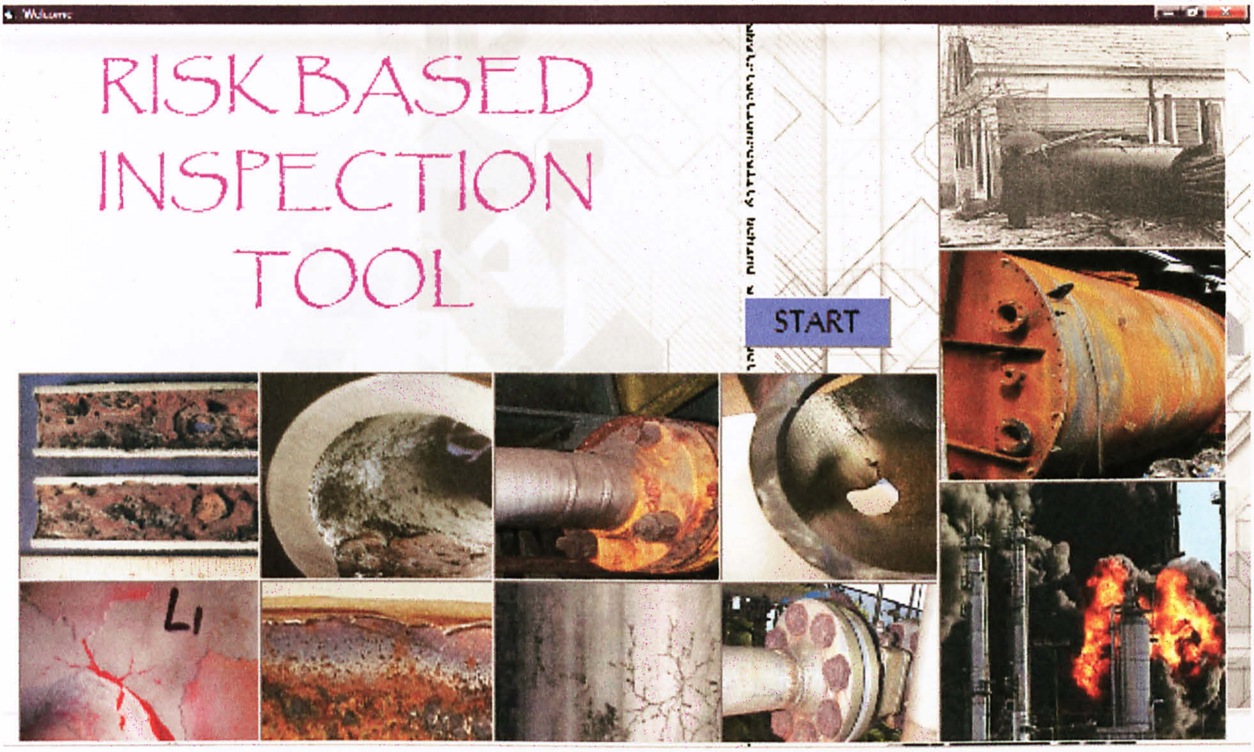


Figure 3: Start Window

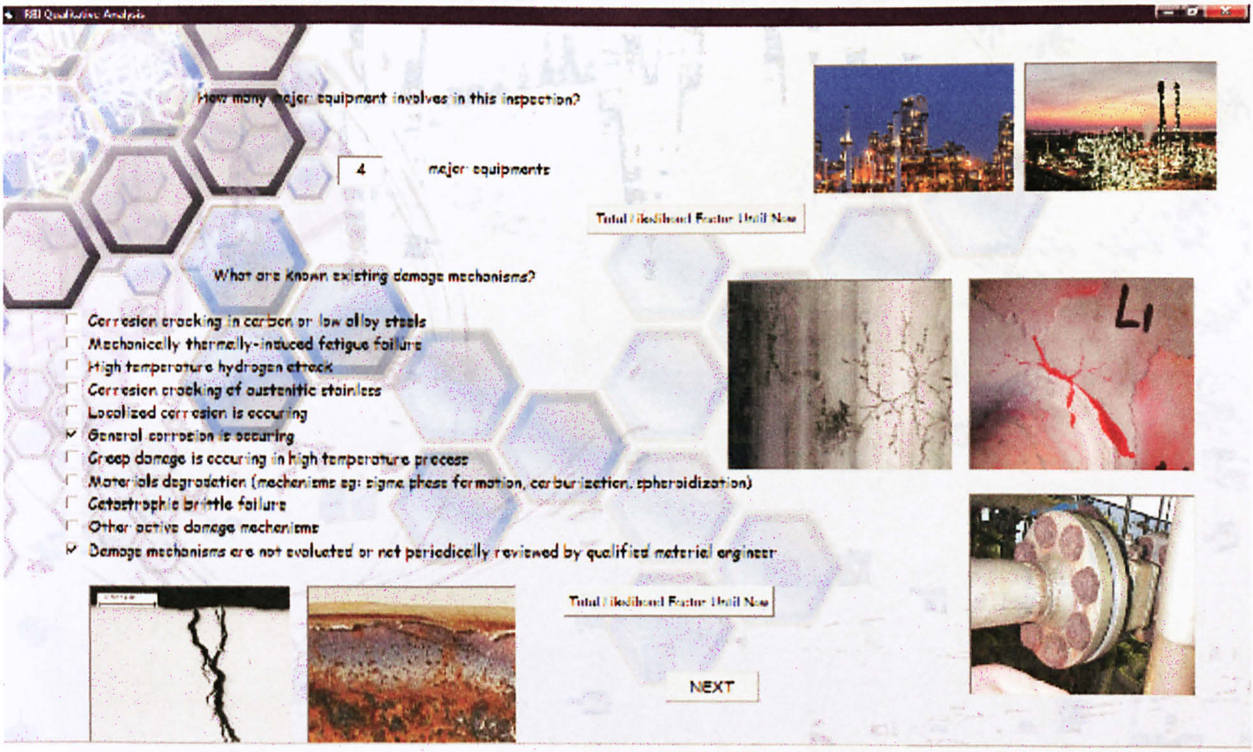


Figure 4: Equipment Factor and Damage Factor for Likelihood Analysis

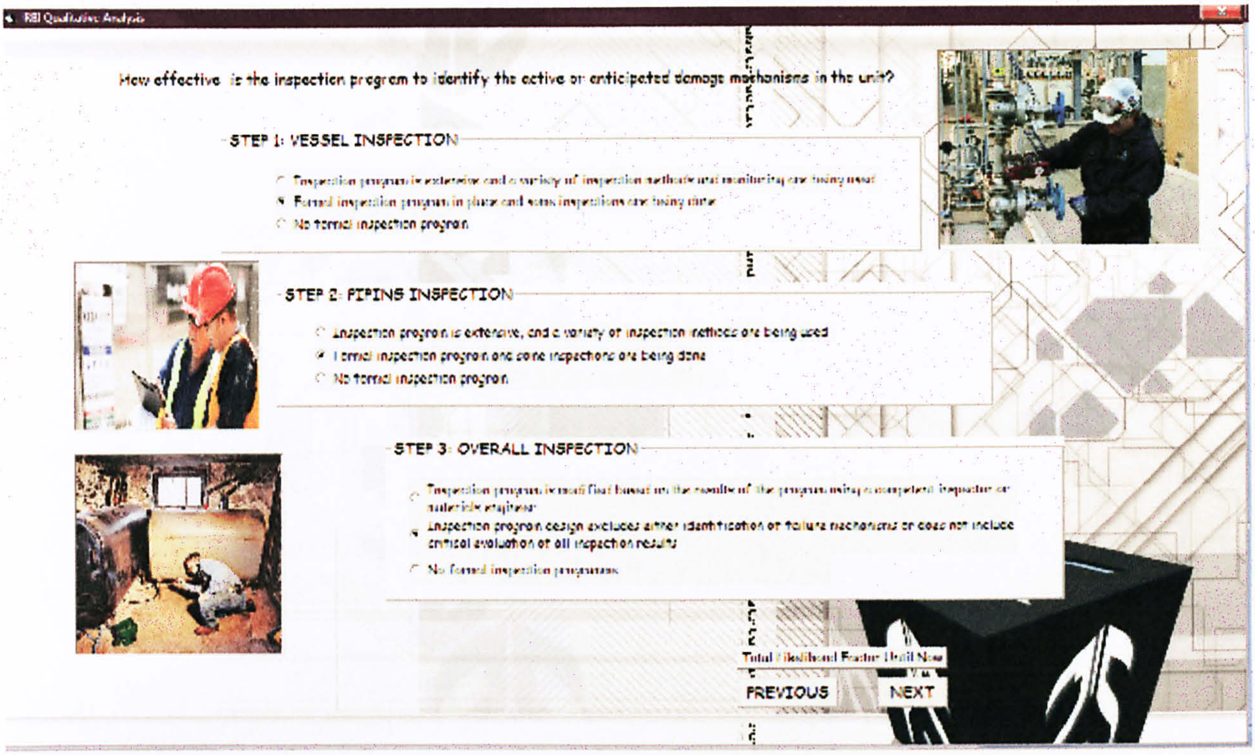


Figure 5: Inspection Factor for Likelihood Analysis

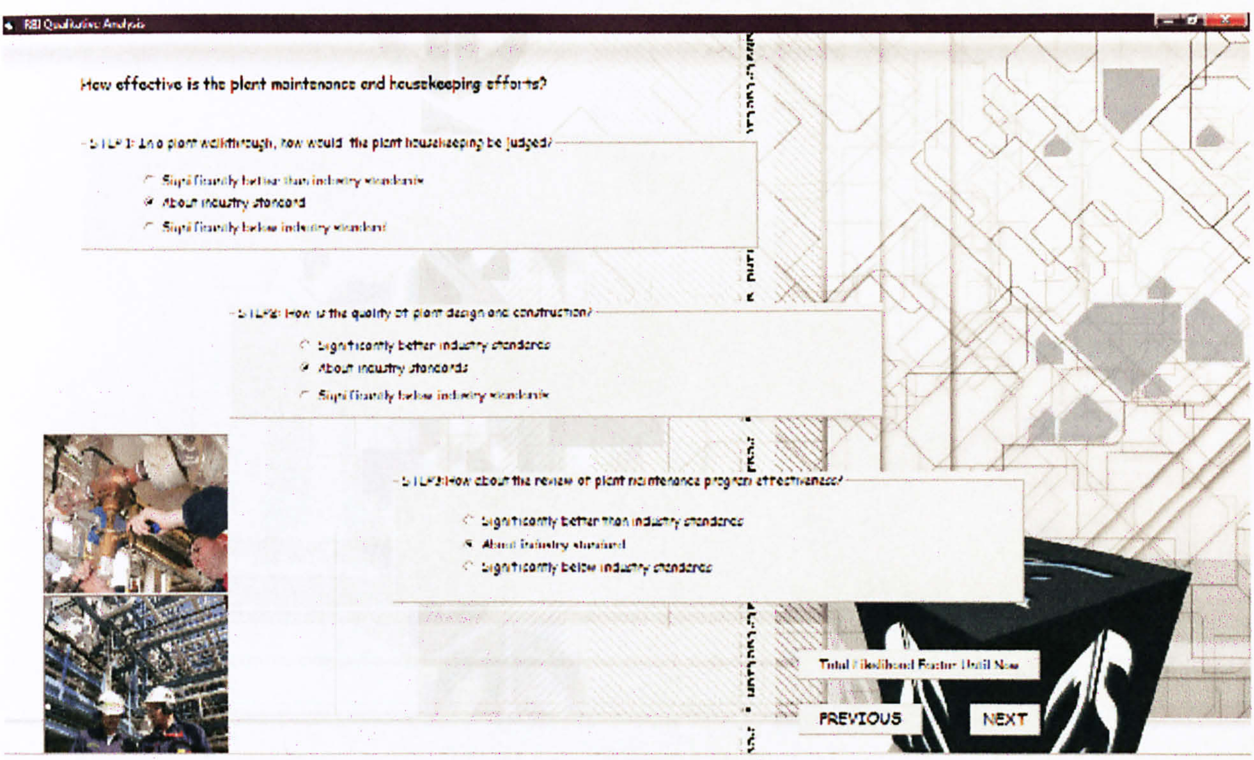


Figure 6: Condition Factor for Likelihood Analysis

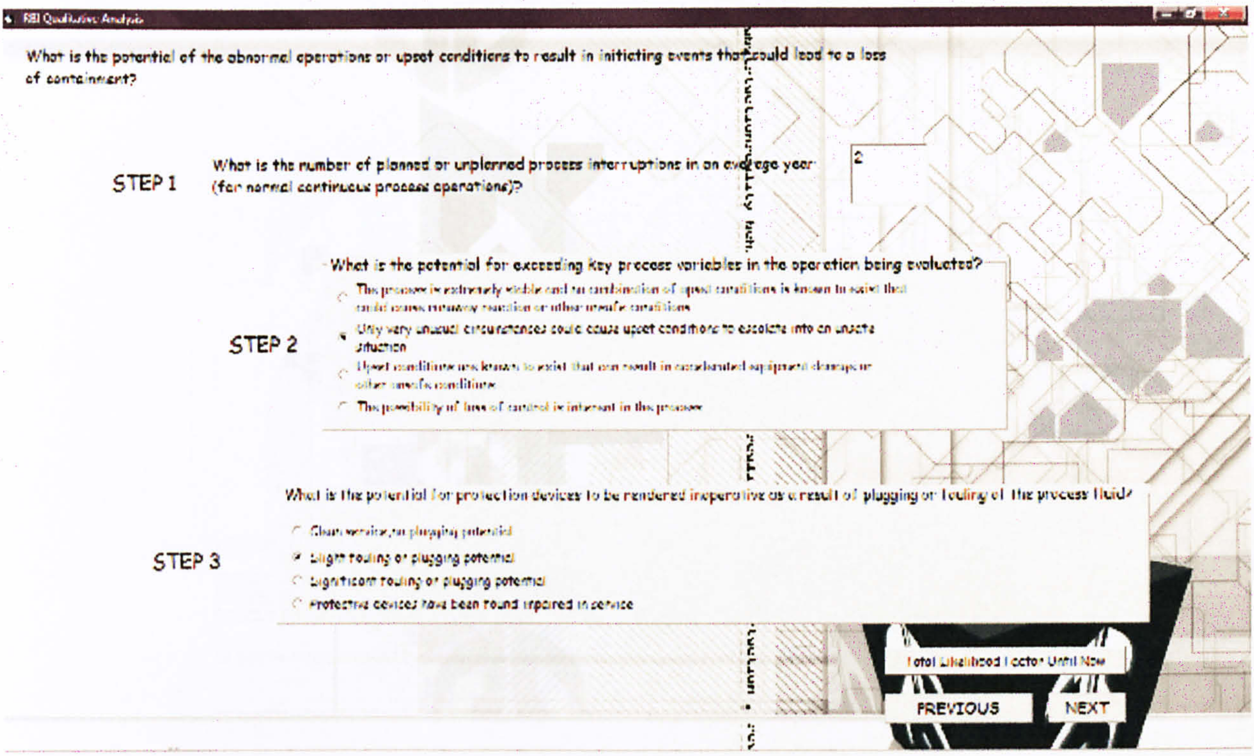


Figure 7: Process Factor for Likelihood Analysis

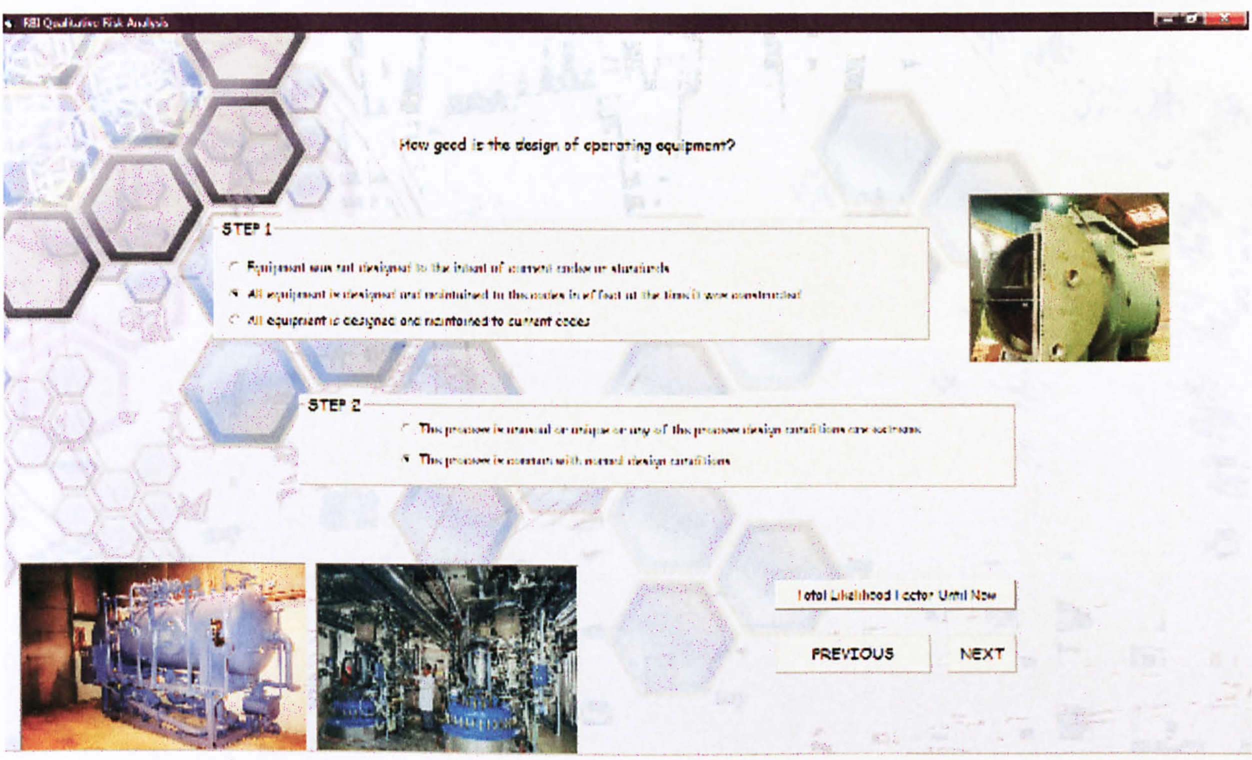


Figure 8: Mechanical Design Factor for Likelihood Analysis

Figure 9: Total Likelihood Factor and Likelihood Category

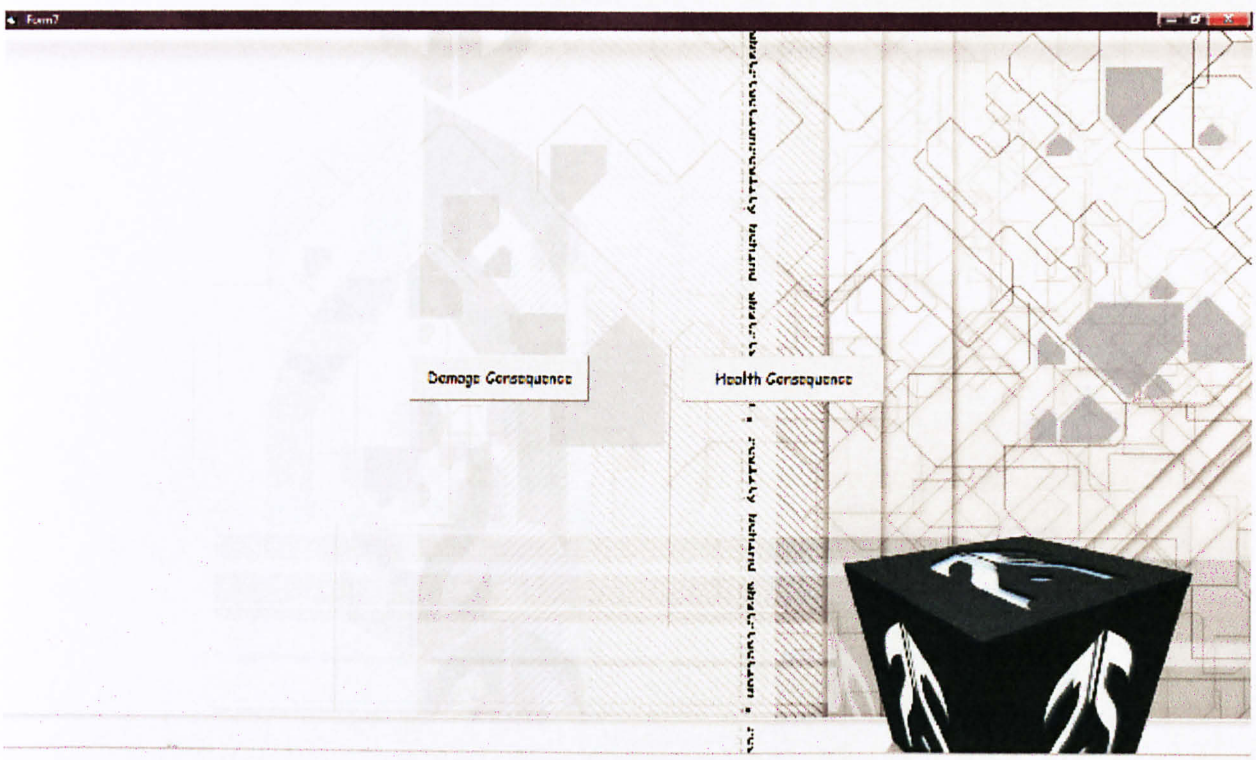


Figure 10: Types of Consequence

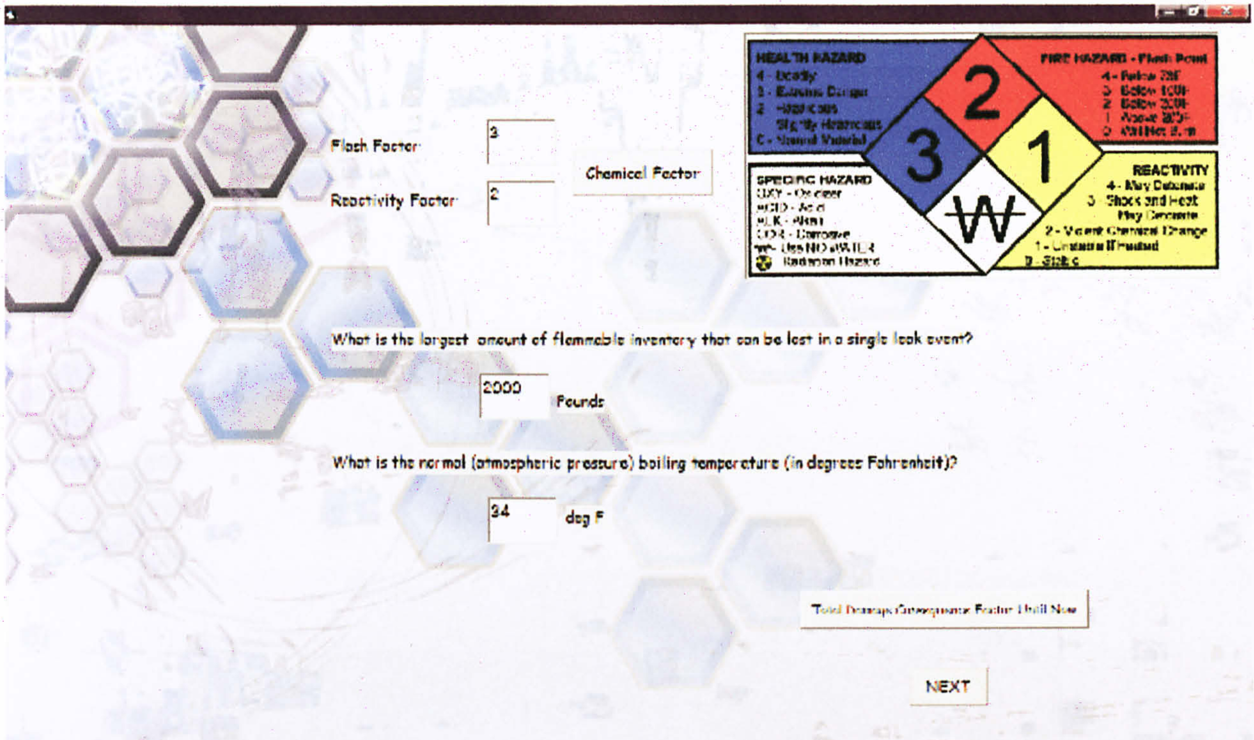


Figure 11: Chemical Factor, Quantity Factor and State Factor for Consequence Analysis

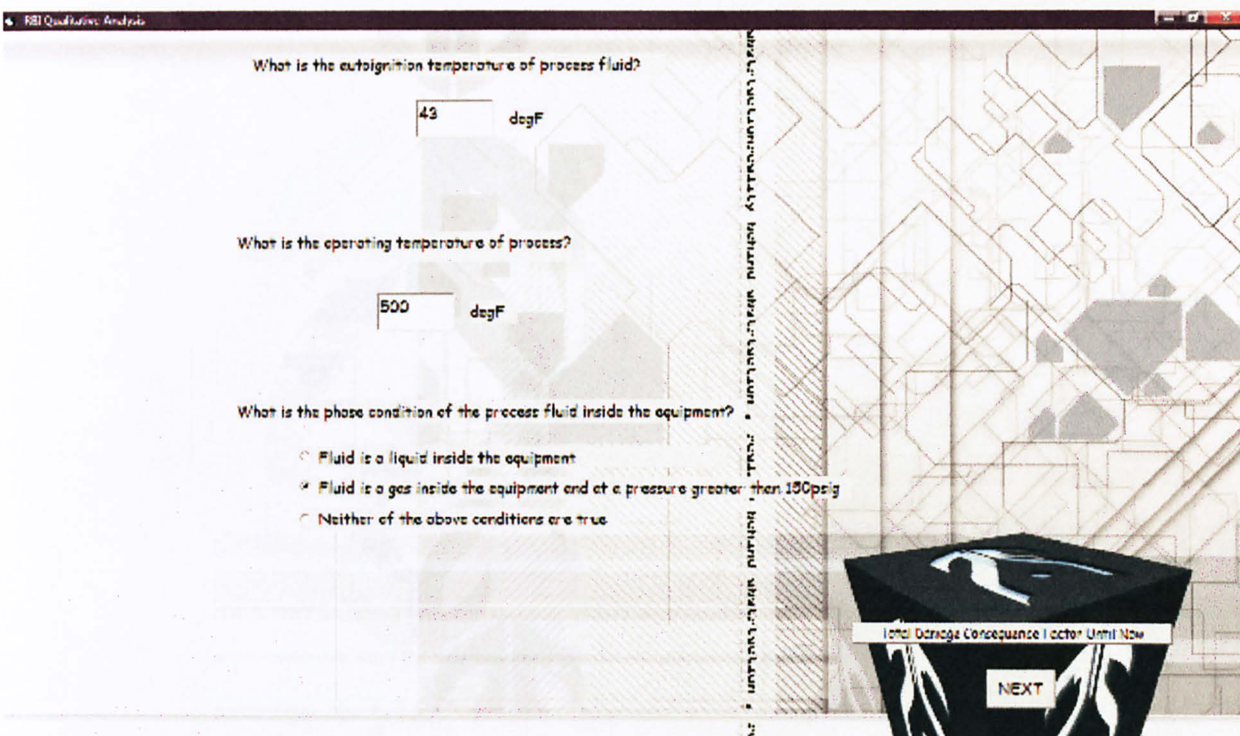


Figure 12: Auto-Ignition Factor and Pressure Factor for Consequence Analysis

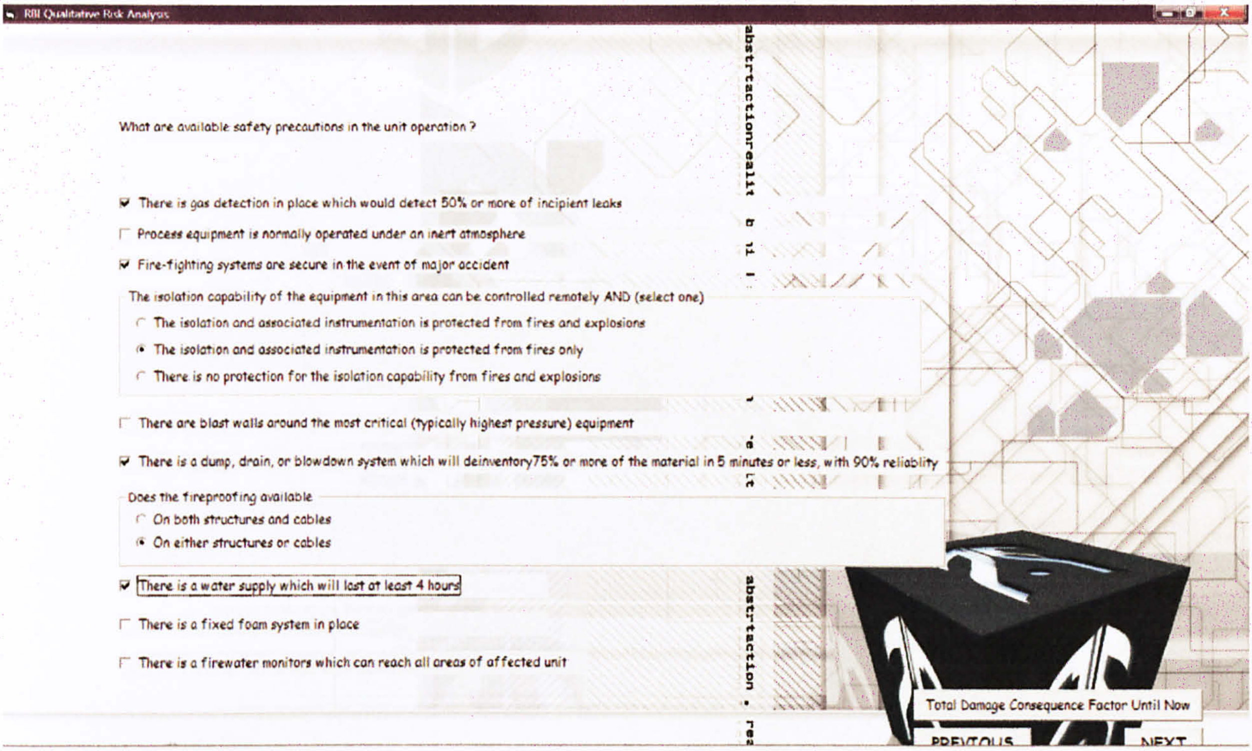


Figure 13: Credit Factor for Consequence Analysis

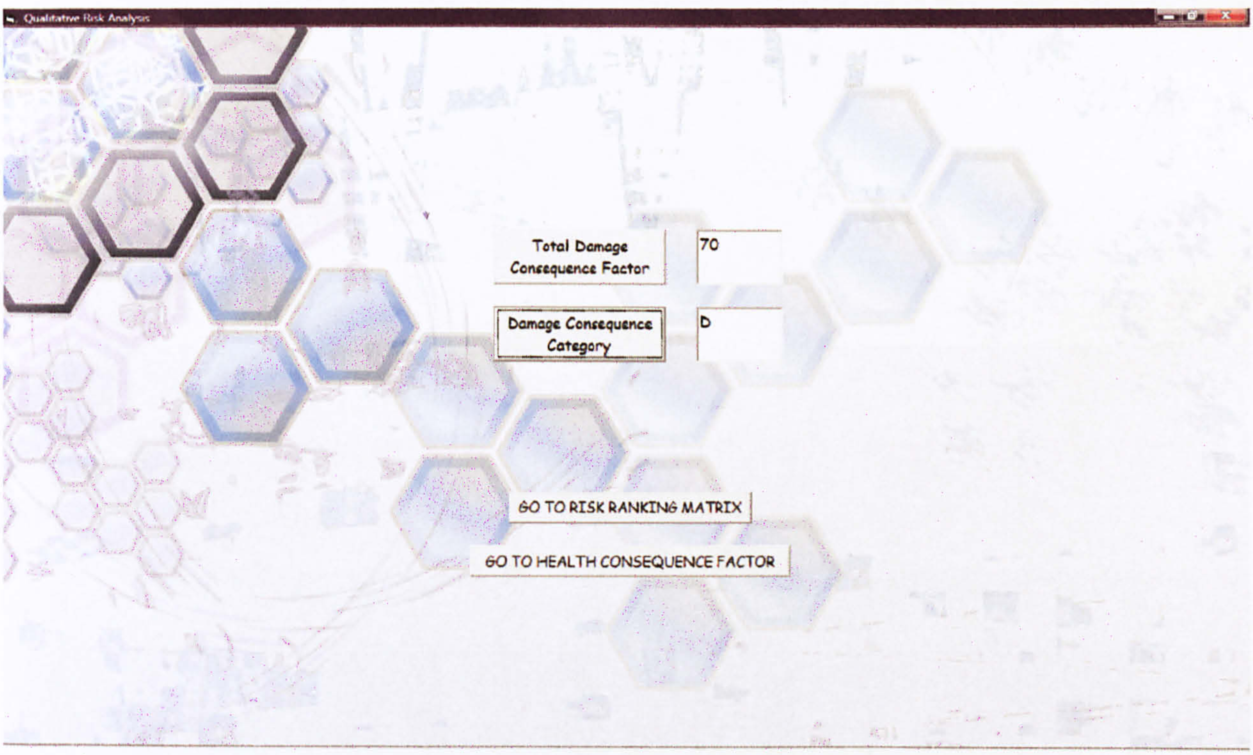


Figure 14: Risk Ranking Matrix for Likelihood and Damage Consequence Analysis

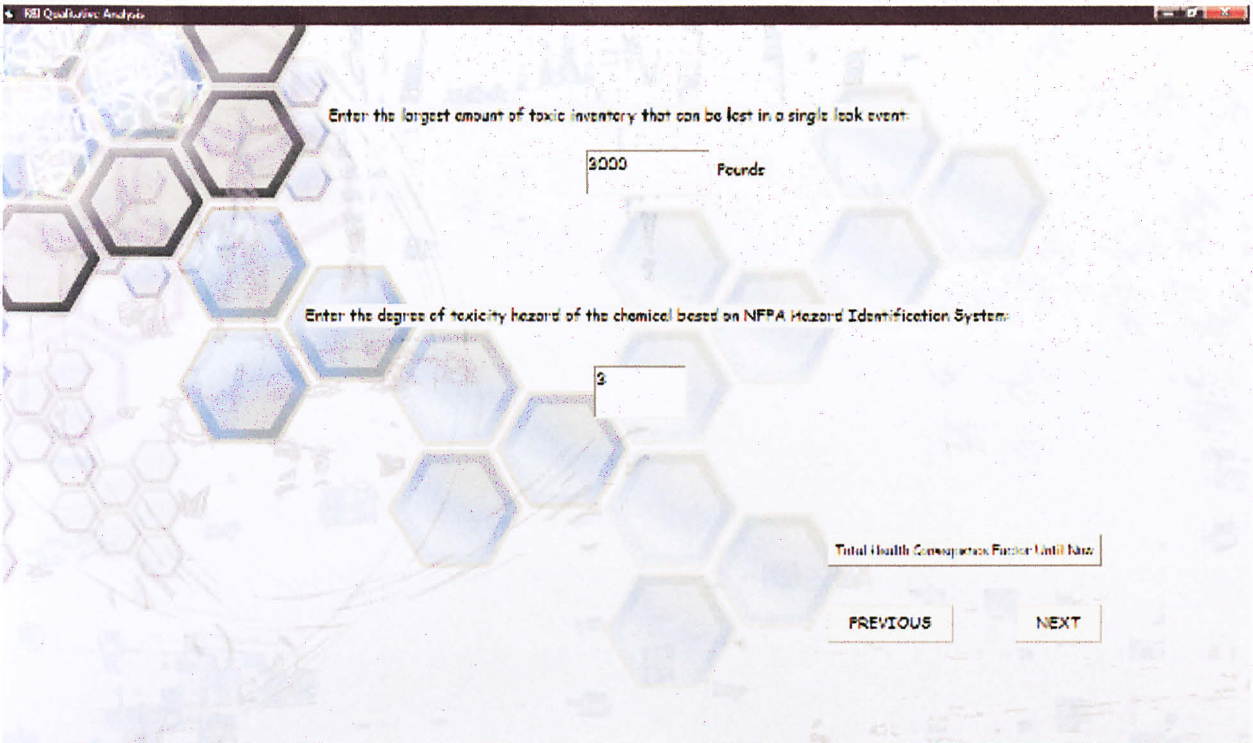


Figure 15: Quantity and Toxicity Factor for Health Consequence Analysis

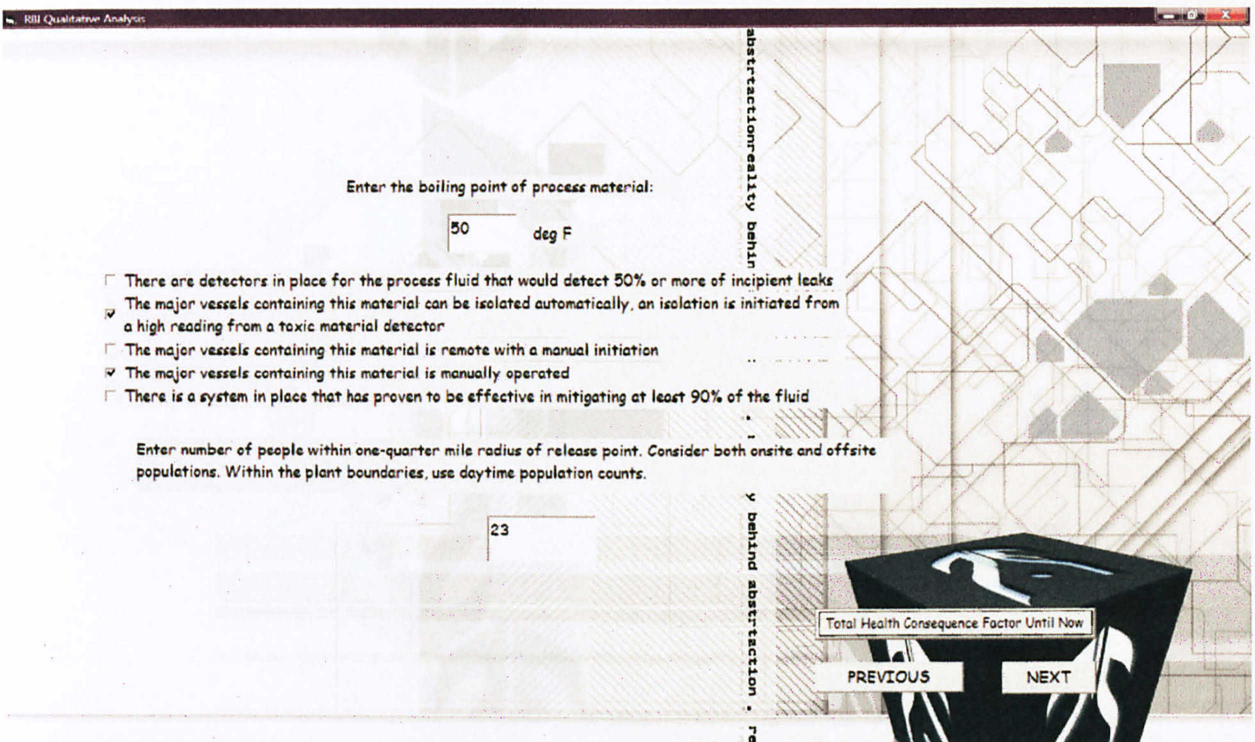


Figure 16: Dispersibility Factor, Credit Factor and Population Factor for Health Consequence Analysis

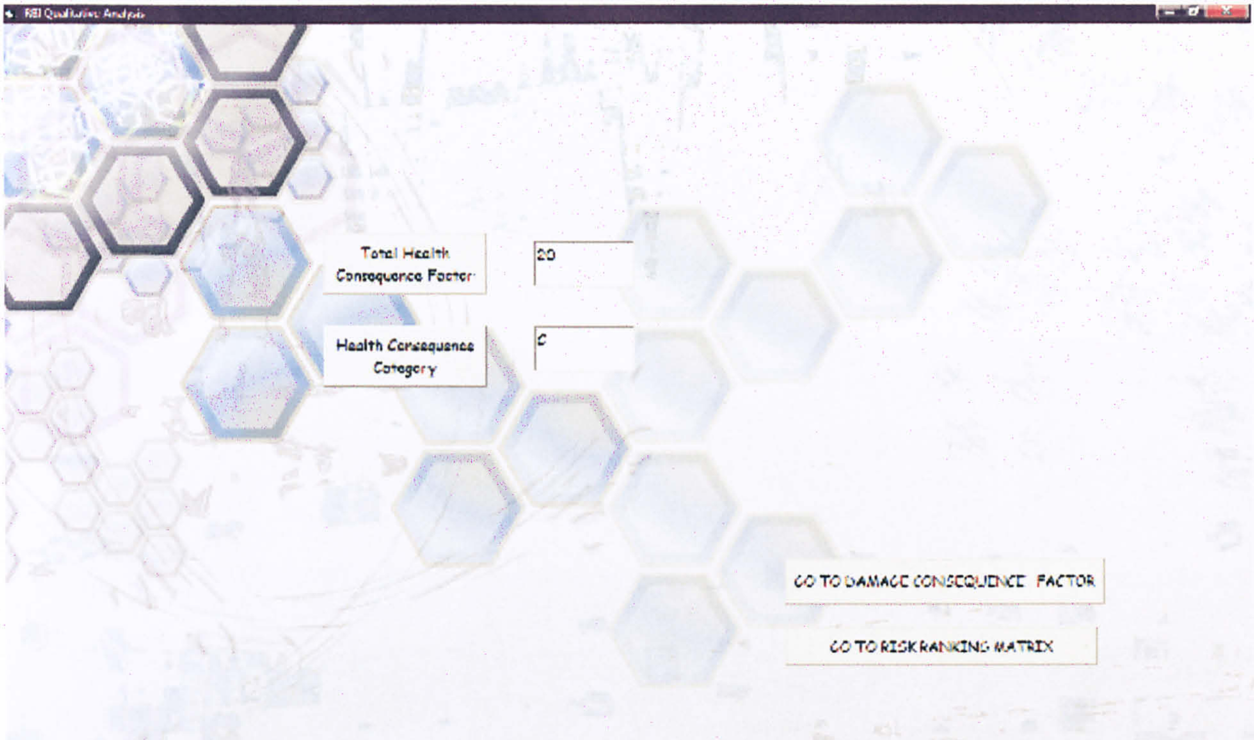


Figure 17: Risk Ranking Matrix for Likelihood and Health Consequence Analysis

3.7 Trial Test on Several Case Studies

There are two different case studies are tested on this system. Please refer to Appendix B for the details.

CHAPTER 4
DISCUSSION

The results from developed RBI Tool are compared to the results from other RBI Tool Software in the industry as the benchmark. The benchmark's system is essentially an implementation of the methodology described in API 581. The approach is semi-quantitative with separate calculation being performed for the likelihood and consequence components for each item of the plant. The results are reported on a 5x5 matrix with likelihood category of 1 to 5 and the consequence category A to E. Thus, the lowest risk category is 1A and the highest risk category 5E. Likelihood analysis is based on the assessment of each of the damage mechanisms and a probability of failure can be determined from the product of a generic failure frequency, the damage factor is based on guidance in API 581 and covers areas including leadership and administration, management of change, operating procedures, safe working practices and training. For mechanisms where data is limited, the guidance in the API technical modules is used. The damage factor for any given mechanism is in turn dependent on the effectiveness of the inspection for that mechanism. Bayes theorem is used to derive a quantitative inspection effectiveness value from a qualitative inspection category. Thus, for a fairly effective inspection procedure (the true damage state is correctly identified 50% of the time) the damage factor and thus the probability of failure increase. A quantitative evaluation of the likelihood of failure in terms of events per year can thus be obtained. Consequence analysis is based on knowledge of the equipment damage, fatality and toxicity areas, the number of outage days together with generic cost data. Consequence data are calculated for a range of hole sizes and weighted based on generic data for the failure frequency for each hole size and the total failure frequency for the equipment item. Risk tolerability criteria are established for each case based on financial and safety risks together with other influences such as applicable regulations, local sensitivities and the legal environment. These criteria establish a target risk level.

This information is obtained from **Risk Based Inspection -A Case Study Evaluation of Onshore Process Plant** by **W Geary.**

Two case studies (Refer to Appendix B) have been run on the developed RBI Tool. The comparison between the results from the developed RBI Tool and the benchmark are as follows:

CASE 1: Molecular Sieve Vessel		
	Qualitative Analysis	**Benchmark**
Likelihood Rank	3	3
Consequence Rank	E	D
Risk	Medium High	High

CASE 2: Autoclave		
	Qualitative Analysis	**Benchmark**
Likelihood Rank	5	2
Consequence Rank	D	A
Risk	High	Low

For the developed RBI Tool, in likelihood category, there are six factors are evaluated that will affect the likelihood of a large leak. Each factor is weighted, and their combination results in the likelihood factor. The six subfactors that make up the likelihood category are as follows:

- The likelihood equipment factor (EF) – is related to the number of components on the unit that have the potential to fail. The EF has a maximum of 15 points.
- The likelihood damage factor (DF) – is a measure of the risk that associated with known damage mechanisms in the unit. These mechanisms include levels of general corrosion, fatigue cracking, low temperature exposure, and high-temperature degradation. This factor receives a maximum value of 20 points in the overall assessment.
- The likelihood in inspection factor (IF) – provides a measure of the effectiveness of the current inspection programme and its ability to identify the active or anticipated damage mechanism in the unit. It examines the types of inspections, their thoroughness, and the management of the inspection programme. The factor is weighted with negative numbers because the quality of the inspection program will partially offset the likelihood of failure

inherent in damage mechanism from damage factors. The maximum weight for the inspection factor is 15 points.

- The likelihood of condition factor (CCF) – accounts for the physical condition of the equipment from a maintenance and housekeeping perspective. A simple evaluation is performed on the apparent condition and upkeep of the equipment from a visual examination. The CCF has a maximum value of 15 points.
- The likelihood process factor (PF) – is a measure of the potential for abnormal operations or upset conditions to initiate a sequence leading to a loss of containment. It is a function of the number of shutdowns or process interruptions (planned or unplanned), the stability of the process, and the potential for failure of protective devices because of plugging or other causes. The PF is weighted at maximum 15 points.
- The likelihood mechanical damage factor (MDF) – measures the safety factor within the design of the unit whether it is designed to current standards, and how unique, complex, or innovative the unit design is. The MF is weighted at 15 points.

For consequence category, there are seven elements are combined:

- The consequence chemical factor (CF) – a chemical's inherent tendency to ignite, is derived as a combination of the material's flash factor and its reactivity factor. Flash factors correspond to the material's NFPA 1 Class rating, while the reactivity factor is a function of how readily the material can explode when exposed to an ignition source.
- The consequence quantity factor (QF) – represents the largest amount of material that could reasonably be expected to be released from a unit in single event. The factor is based on the largest mass (in pounds) of flammable inventory in the unit.
- The consequence state factor (SF) – is a measure of how readily a material will flash to a vapour when it is released to the atmosphere. It is determined from a ratio of the average process temperature to the boiling temperature at atmospheric pressure (using absolute temperatures in the ratio)
- The consequence auto-ignition factor – is incorporated to account for the increased probability of ignition for a fluid released at a temperature above auto-ignition temperature.
- The consequence pressure factor (PRF) – is a measure of how quickly the fluid can escape.

- The consequence credit factor (CRF) – is determined to account for the safety features engineered into the unit. These safety features can play a significant role in reducing the consequence of potentially catastrophic release.
- The damage potential factor (DMF) – the potential for fire or explosion to cause damage to the equipment near large inventory or flammable or explosive materials.

The damage consequence category is then found by combining the above consequence factors and selecting the category based on ranges of these combined factors.

If there is health consequence, the following factors are considered:

- The toxic quantity factor (TQF) – is a measure of both the quantity and the toxicity of a material.
- The dispersibility factor (DIF) – is a measure of the ability of a material to disperse. It is determined directly from the normal boiling points of the material. The higher the boiling point, the less likely material is to disperse.
- The credit factor (CRF) – is determined to account for the safety features engineered into the unit.
- The population factor (PPF) – is a measure of the number of people that can potentially be affected by a toxic release event.

The health consequence category is then found by combining the above consequence factors and selecting the category based on ranges of these combined factors.

The consequence categories (health and damage) are assigned letter scores, and the one with the higher value is considered for risk rating.

For benchmark's system in case study 1, two separate analyses were performed, one for the process mode and one for the regeneration mode. Based on the inspections carried out in 1986, 1992 and 2000 it was assumed that the thinning mechanism was of minor importance and a corrosion rate of 0.01 mm/year was assigned. Thus a thinning damage factor for the process condition was 1.7 and for the regeneration condition was 0.2.

External pitting attack to a depth of 0.5 mm was found during the inspection in 2000 and it was assumed that a representative corrosion rate of 0.028 mm/year was appropriate. Based on this information an external damage factor of 1.7 and 0.2 was calculated for the process and regeneration modes respectively.

Additional information was requested by the participant to allow calculations of stress corrosion cracking (SCC) to be carried out. The assessment for SCC was based on guidance presented in API 581. The susceptibility was derived from tables of pH and H_2S content. The post-weld heat treated hardness (assumed) was also taken into account. On this basis the vessel was rated as not susceptible. The pH, H_2S content and the sulphur level of the steel were used to determine the material susceptibility to hydrogen induced cracking (HIC) and stress oriented hydrogen induced cracking (SOHIC), again from tables in API 581. This showed that the vessel had a low susceptibility to these mechanisms.

These data produced a calculated likelihood of failure values of 6.5E-03 and 78E-05 per year for the process and regeneration modes respectively. For the purposes of this assessment a future risk evaluation target date of December 31st 2010 was assumed. This resulted in a change in the likelihood of failure values to 1.6E-02 and 7.8E-05 per year for the process and regeneration modes respectively. The regeneration likelihood data remained unchanged since no damage mechanisms are active.

The assessment found that HIC was an active mechanism during the process phase, which led to the increase in the likelihood of failure, and proposed that a highly effective inspection method be used for this mechanism within the next 3 years. Highly effective was defined as a method that will correctly identify the anticipated degradation in 90% of cases. Specifically, an intrusive inspection of the surface area, 95% to 100% wet fluorescent magnetic particle (WFMP) with UT follow up of any indications. Alternatively, a non-intrusive inspection could be carried out using manual or automated UT of 95% to 100% of the external surface.

The recommendation was based on the high risk outcomes especially for the future evaluation date. The high risk was primarily associated with the increase in likelihood of failure with time but also with the high consequences calculated. For the consequence analysis calculations, methane was chosen as the representative chemical and H_2S as the toxic chemical. Look-up methane was chosen as the representative chemical and H_2S as the toxic chemical. Look-up tables were used to provide consequence solutions for small, medium and large holes and for complete rupture. Data was derived for the equipment damage area, the fatality area, the toxicity area, the number of outage days, the business interruption costs, the equipment damage costs and the safety costs. The results were weighted based on generic failure frequency data and a total cost was calculated as £58M. The majority of the consequence cost was associated with the flammability of methane rather than the toxic consequences of the H_2S. The consequence costs were calculated separately for the regeneration mode and a value of £16M was obtained primarily associated with the lower regeneration pressure.

For benchmark's system in case study 2, Corrosion and chloride SCC were considered to be the active damage mechanisms in this vessel. Based on the inspection results in 1987 and 1989 it was assumed that thinning phenomena were of minor importance. Therefore, a corrosion rate of 0.01mm/year was assigned.

SCC was addressed using a cracking susceptibility option in the software. An external damage factor was calculated based on a limit state equation derived from structural reliability theory and linear elastic fracture mechanics. Since the jacket space had been inspected in 1987, the confidence in the external damage was fixed at 81.4%. The likelihood of failure, taking into account the damage factor and generic failure frequencies, was calculated to be 5.7E-04.

The same calculation, based on 31/12/2010, gives an increase in the likelihood of failure to 9.8E-04. Thus a likelihood category of 2 was calculated. The consequence calculation was based on business interruption costs only on the grounds that PTFE represented a low fire hazard. A business interruption of 2 days and equipment damage costs of £22k was assumed, thus the total consequence costs were estimated to be £27k giving a consequence category of A. Therefore the risk associated with failure was assigned a "low" category.

It was concluded that an inspection should not be carried out in the short term since the total risk was only slightly reduced and remained low at the future date. Thus it was recommended that the maximum inspection interval should be 10 years. An inspection plan was not submitted.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

RBI Tool is developed by using published methodology from API 581. Risk analysis of the equipments is evaluated by considering the likelihood and consequence of failure. Only qualitative risk analysis is developed in this tool. The results of this analysis are validated by comparing to the benchmark.

For different RBI Tool analysis, the risks are slightly different. The amount of information being supplied to the different analysis levels is the main reason to this variation. The concept of each analysis level has been discussed in Chapter 3 of this report in order to identify the differences of these two RBI analysis levels.

This developed RBI Tool is only a prototype. The methodology has followed the published guideline from API 581. This tool has the potential to be further developed and used in the real plant.

REFERENCES

[1] API, Risk Based Inspection Based Resource Document, API Publication 581, May 2000

[2] API, Risk Based Inspection, API Recommended Practice 580, May 2002

[3] American Bureau of Shipping (2003). *Guide for Surveys Using Risk-Based Inspection for the Offshore Industr.*

[4] Teo Yong Seng & Gery Koch (2006). *Integrated Risk Based Inspection (RBI) And IDS (Inspection Databank System) Software Approach*

[5] W Geary (2002). Risk Based Inspection – A Case Study Evaluation on Onshore Process Plant.

[6] A.Raman W (2007). An Integrity Assessment of Corroding Pipeline Using Shell 92 Code (Bachelor of Engineering (Hons) Dissertation, Universiti Teknologi Malaysia, 2007)

[7] Institution of Engineering and Technology (January 2007). Risk-Based Inspection. Health & Safety Briefing No. 27.

APPENDICES

Appendix A

Table A. 1: Guidelines for Determining the Phase of a Fluid

Phase of Fluid at Steady-State Operating Conditions	Phase of Fluid at Steady-State Ambient Conditions	Determination of Final Phase for Consequence Calculation
gas	gas	model as gas
gas	liquid	model as gas
liquid	gas	model as gas *unless* the fluid boiling point at ambient conditions is greater than 80°F, then model as a liquid
liquid	liquid	model as liquid

Table A. 2: Detection and Isolation System Rating Guide

Type of Detection System	Detection Classification
Instrumentation designed specifically to detect material losses by changes in operating conditions (i.e., loss of pressure or flow) in the system.	A
Suitably located detectors to determine when the material is present outside the pressure-containing envelope.	B
Visual detection, cameras, or detectors with marginal coverage	C
Type of Isolation System	**Isolation Classification**
Isolation or shutdown systems activated directly from process instrumentation or detectors, with no operator intervention.	A
Isolation or shutdown systems activated by operators in the control room or other suitable locations remote from the leak.	B
Isolation dependent on manually-operated valves	C

Table A. 3: Leak Durations Based on Detection and Isolation Systems

Detection System Rating	Isolation System Rating	Leak Duration
A	A	20 minutes for $^1/_4$-inch leaks 10 minutes for 1-inch leaks 5 minutes for 4-inch leaks
A	B	30 minutes for $^1/_4$-inch leaks 20 minutes for 1-inch leaks 10 minutes for 4-inch leaks
A	C	40 minutes for $^1/_4$-inch leaks 30 minutes for 1-inch leaks 20 minutes for 4-inch leaks
B	A or B	40 minutes for $^1/_4$-inch leaks 30 minutes for 1-inch leaks 20 minutes for 4-inch leaks
B	C	1 hour for $^1/_4$-inch leaks 30 minutes for 1-inch leaks 20 minutes for 4-inch leaks
C	A, B, or C	1 hour for $^1/_4$-inch leaks 40 minutes for 1-inch leaks 20 minutes for 4-inch leaks

Table A. 4: Continuous Release Consequence Equations – Auto Ignition Not Likely[a]

Material	Final Phase Gas		Final Phase Liquid	
	Area of Equipment Damage (ft^2)	Area of Fatalities (ft^2)	Area of Equipment Damage (ft^2)	Area of Fatalities (ft^2)
C_1–C_2	$A = 43\,x^{0.98}$	$A = 110\,x^{0.96}$		
C_3–C_4	$A = 49\,x^{0.98}$	$A = 125\,x^{0.96}$		
C_5	$A = 25.2\,x^{0.98}$	$A = 62.1\,x^{1.00}$	$A = 536\,x^{0.90}$	$A = 1544\,x^{0.90}$
C_6–C_8	$A = 29\,x^{0.98}$	$A = 68\,x^{0.96}$	$A = 182\,x^{0.89}$	$A = 516\,x^{0.89}$
C_9–C_{12}	$A = 12\,x^{0.98}$	$A = 29\,x^{0.96}$	$A = 130\,x^{0.90}$	$A = 373\,x^{0.89}$
C_{13}–C_{16}			$A = 64\,x^{0.90}$	$A = 183\,x^{0.89}$
C_{17}–C_{25}			$A = 20\,x^{0.90}$	$A = 57\,x^{0.89}$
C_{25}+			$A = 11\,x^{0.91}$	$A = 33\,x^{0.89}$
H_2	$A = 198\,x^{0.992}$	$A = 614\,x^{0.933}$		
H_2S	$A = 32\,x^{1.00}$	$A = 52\,x^{1.00}$		
HF				
Aromatics	$A = 121.39\,x^{0.8911}$	$A = 359\,x^{0.8821}$		
Styrene	$A = 121.39\,x^{0.8911}$	$A = 359\,x^{0.8821}$		

Table A. 5: Instantaneous Release Consequence Equations -Auto Ignition Not Likely[a]

Material	Final Phase Gas		Final Phase Liquid	
	Area of Equipment Damage (ft^2)	Area of Fatalities (ft^2)	Area of Equipment Damage (ft^2)	Area of Fatalities (ft^2)
C_1–C_2	$A = 41\,x^{0.67}$	$A = 79\,x^{0.67}$		
C_3–C_4	$A = 28\,x^{0.72}$	$A = 57.7\,x^{0.75}$		
C_5	$A = 13.4\,x^{0.73}$	$A = 20.4\,x^{0.76}$	$A = 1.49\,x^{0.85}$	$A = 4.34\,x^{0.85}$
C_6–C_8	$A = 14\,x^{0.67}$	$A = 26\,x^{0.67}$	$A = 4.35\,x^{0.78}$	$A = 12.7\,x^{0.78}$
C_9–C_{12}	$A = 7.1\,x^{0.66}$	$A = 13\,x^{0.66}$	$A = 3.3\,x^{0.76}$	$A = 9.5\,x^{0.76}$
C_{13}–C_{16}			$A = 0.46\,x^{0.88}$	$A = 1.3\,x^{0.88}$
C_{17}–C_{25}			$A = 0.11\,x^{0.91}$	$A = 0.32\,x^{0.91}$
C_{25}+			$A = 0.03\,x^{0.99}$	$A = 0.081\,x^{0.99}$
H_2	$A = 545\,x^{0.657}$	$A = 982\,x^{0.652}$		
H_2S	$A = 148\,x^{0.63}$	$A = 271\,x^{0.63}$		
HF				
Aromatics	$A = 2.26\,x^{0.8227}$	$A = 10.5\,x^{0.7583}$		
Styrene	$A = 2.26\,x^{0.8227}$	$A = 10.5\,x^{0.7583}$		

Note: Shaded area represents cases in which equations are nonapplicable.
x = total release mass, lb.
A = area, ft^2.

[a]Not likely if process temperature is less than auto ignition temperature plus 80°F.

Table A. 6: Continuous Release Consequence Equations - Auto Ignition Likely[a]

Material	Final Phase Gas		Final Phase Liquid	
	Area of Equipment Damage (ft^2)	Area of Fatalities (ft^2)	Area of Equipment Damage (ft^2)	Area of Fatalities (ft^2)
C_1–C_2	$A = 280\,x^{0.95}$	$A = 745\,x^{0.92}$		
C_3–C_4	$A = 315\,x^{1.00}$	$A = 837\,x^{0.92}$		
C_5	$A = 304\,x^{1.00}$	$A = 811\,x^{1.00}$		
C_6–C_8	$A = 313\,x^{1.00}$	$A = 828\,x^{1.00}$	$A = 525\,x^{0.95}$	$A = 1315\,x^{0.92}$
C_9–C_{12}	$A = 391\,x^{0.95}$	$A = 981\,x^{0.92}$	$A = 560\,x^{0.95}$	$A = 1401\,x^{0.92}$
C_{13}–C_{16}			$A = 1023\,x^{0.92}$	$A = 2850\,x^{0.90}$
C_{17}–C_{25}			$A = 861\,x^{0.92}$	$A = 2420\,x^{0.90}$
C_{25}+			$A = 544\,x^{0.90}$	$A = 1604\,x^{0.90}$
H_2	$A = 1146\,x^{1.00}$	$A = 3072\,x^{1.00}$		
H_2S	$A = 203\,x^{0.89}$	$A = 375\,x^{0.94}$		
HF				
Aromatics				
Styrene				

Shaded area represents cases in which equations are nonapplicable.
x = total release rate, lb/sec.
A = area, ft^2.

[a]Must be processed at least 80°F above auto ignition temperature.

Table A. 7: Instantaneous Release Consequence Equations - Auto Ignition Likely[a]

Material	Final Phase Gas		Final Phase Liquid	
	Area of Equipment Damage (ft^2)	Area of Fatalities (ft^2)	Area of Equipment Damage (ft^2)	Area of Fatalities (ft^2)
C_1–C_2	$A = 1079\,x^{0.62}$	$A = 3100\,x^{0.63}$		
C_3–C_4	$A = 523\,x^{0.63}$	$A = 1768\,x^{0.63}$		
C_5	$A = 275\,x^{0.61}$	$A = 959\,x^{0.63}$		
C_6–C_8	$A = 76\,x^{0.61}$	$A = 962\,x^{0.63}$		
C_9–C_{12}	$A = 281\,x^{0.61}$	$A = 988\,x^{0.63}$	$A = 6.0\,x^{0.53}$	$A = 20\,x^{0.54}$
C_{13}–C_{16}			$A = 9.2\,x^{0.88}$	$A = 26\,x^{0.88}$
C_{17}–C_{25}			$A = 5.6\,x^{0.91}$	$A = 16\,x^{0.91}$
$C_{25}+$			$A = 1.4\,x^{0.99}$	$A = 4.1\,x^{0.99}$
H_2	$A = 1430\,x^{0.618}$	$A = 4193\,x^{0.621}$		
H_2S	$A = 357\,x^{0.61}$	$A = 1253\,x^{0.63}$		
HF				
Aromatics				
Styrene				

Shaded area represents cases in which equations are nonapplicable.
x = total release mass, lb.
A = area, ft^2.

[a]Must be processed at least 80°F above auto ignition temperature.

Appendix B

Case 1

Molecular sieve vessel

BACKGROUND/ADDITIONAL INFORMATION

Molecular sieve vessel commissioned in 1982. Design standard BS 5500.Design thickness 107mm (actual 109mm), diameter 2374mm, length 16000mm. Corrosion allowance 4mm. Temperature: max design 350°C, min design –62°C, max op 320°C, min op 0°C.
Pressure: max design 121 barg, min design 0 barg, max operating 115 barg, normal operating 110 barg.

	Assessment Details	
	Likelihood Information	
1	**Number of units and type of plant:**	**One of four sister vessels**
2	**Plant function:**	**Molecular sieve vessel**
3	**Plant processes:**	**Natural gas: absorb H_2S and H_2O** **Process 110 barg, 6°C** **Regeneration using hot gases at 70 barg at 310°C.**
4	**Process stability:**	**Continuous treatment process alternating between absorption at 6 Deg C and regeneration at 310 Deg C .** **Process is considered stable.**
5	**Material of construction:**	**Low temperature Carbon steel** **Grade BS 1501-225-490B-LT62**
6	**Damage mechanisms:**	**Internally: General corrosion** **Pitting corrosion** **Hydrogen induced cracking** **Sulphide SCC** **Externally: General corrosion** **Pitting corrosion** **Bottom dished end is internally protected by SS thermal shield petals.**
7	**Design standards:**	**BS5500**
8	**Inspection:**	**1986 Partial visual internal – good condition, light millscale in some isolated areas**

		1992 100% internal – 19 surface breaking linear flaws in ground weld caps, removed by light grinding, considered to be from manufacture (slag lines). 2000 External. Coating and insulation material removed – light surface corrosion, isolated areas of rust scaling. Pitting to 0.5mm depth. Nozzles and shell welds including skirt to shell - MPI – no defects. *2000 Internal (non intrusive). 16% surface area UT scans for internal* pitting – shell, dome ends, all nozzles – no defects. Wall thickness measurements satisfactory. Upper (1992) internal support ring weld UT scanned 100% circumference and lower original ring 25% circumference and no defects were detected.
9	Plant maintenance history:	1992 Additional grid and support beams welded into vessel 2000 Vessel totally delagged for refurbishment of coating and insulation material.
10	Process protection devices:	Unit 2600 is protected by a pressure control valve, high pressure trip, primary relief valves and secondary relief valves sized in accordance with API RP 520. This vessel is protected by three relief valves.
	Consequence Information	
11	Fire:	Emergency response procedures. External fire fighting resources would be required for the most serious event.
12	Incident mitigation:	H2S and flammable gas detection. ESD and blowdown facilities. Control of ignition sources. Hazardous Area classification reduces the ignition probability of unignited vapour releases. The hazardous area classification zone 2 (H_2S) covers the whole U2600 area. The surrounding area is categorised Zone 2 for hydrocarbon releases. Firewater for cooling. An auto deluge system is provided to process vessels. There are a number of hydrants that may also be used. Firewater fed via electric and diesel fire pumps from site firepond. Emergency response procedures.
13	Chemical data:	Predominantly methane gas – explosive within explosive range in air.
14	Quantity:	7.5 tonnes
15	Chemical state:	Hydrocarbon gas with trace amounts of H2S and water.
16	Commercial damage	Failure would result in moderate total cost (system shut down

	potential:	**resulting in a reduced throughput and significant repair costs.**
17	**Toxicity:**	**Toxic fluids: >0.5 tonnes. Materials on very short exposure could result in death or major injury.** **H2S area authorisation in place. Gas detection and emergency procedures in place.**
18	**Population:**	**Has the potential to cause *minor* effect off site.**

Case 2

Autoclave

BACKGROUND/ADDITIONAL INFORMATION

Vessel manufactured in 1980.
Design temperature 100°C, design pressure 25.85 Barg
Operating temperature 8°C to 95°C (75°C to 50°C jacket), operating pressure 10 Barg (2.75 Barg jacket).
Vessel dimensions: 5'0'' dia. x 11'0'' long SS reactor vessel 1'' wall thickness.
Flanged jacket 3/8'' thick. Carbon Steel.

	Assessment Details	
	Likelihood Information	
1	**Number of units and type of plant**:	***Single unit PTFE reactor and cooling water jacket***
2	**Plant function**:	
3	**Plant processes**:	Reactor filled with water at 75°C and pressure tested to 10 Barg. The pressure is released, water is then agitated and a vacuum pulled to evacuate air from the ullage space. The ammonium sulphate solution catalyst is then injected. TFE is introduced as a gas and is immediately polymerised through water. The temperature of the exothermic reaction is controlled by the cooling water jacket; initially at a temperature of 75°C. reducing to 15°C.
4	**Process stability:**	**Batch process, 3 cycles/day x 48 weeks/year. No process excursions**
5	**Material of construction**:	**321 Stainless steel (carbon steel jacket)**
6	**Damage mechanisms**:	**Stress Corrosion Cracking.** Jacket cooling water Chloride readings: 12 ppm. It is within the temperature susceptibility range for 'Stress Corrosion Cracking. > 60 deg C. In the event of a leak the cooling water recirculates, at the point of discharge it is drawn into a cubicle any PTFE present would be picked up by sensitive 'sniffers'. (1 PPM) Any small leak would render pulling a vacuum, essential element of each batch process, impossible.

		Fatigue and jacket interspace **corrosion** considered no problems to date
7	**Design standards**:	**BS5500**
8	**Inspection:**	Generally very sound. Main problems caused by mechanical damage from agitator. Fell in 1997, surface crack detection revealed nothing significant. Some scarring little worse than scratches 0.5 mm deep. Branch welds not high integrity some original manufacturing defects identified and repaired. Following 'decomposition' in 1989, extensive surface crack detection revealed no problems. Failure of Jacket bolts in 1987 misalignment caused fatigue. Unusual but not repeated! Jacket space examined in 1987 found satisfactory.
9	**Plant maintenance history**:	No repairs or modifications other than those reported under Section 8
10	**Process protection devices:**	The relief streams have never been blocked or restricted. The system has a bursting disc.
	Consequence Information	
11	**Fire**:	No external fire fighting services would be required.
12	**Incident mitigation**:	Gas detection systems are strategically placed in the missile proof cubicle in which it resides.
13	**Chemical data:**	Low fire hazard with PTFE.
14	**Quantity:**	The worst event would be a leak before break situation from the reactor to the jacket. This would be picked up by sniffer systems on the water discharge within the cubicle.
15	**Chemical state:**	Not applicable for PTFE.
16	**Commercial damage potential:**	**Business interruption cost £3k/day.** **Replacement cost £30k**
17	**Toxicity:**	Exposure to fume can lead to short term influenza type systems lasting 48 hours.
18	**Population:**	100 people within 500m of release (on site and off site).

Appendix C

Table C.1: Degradation Mechanisms, Causes and Inspection Methods

Degradation Mechanism	*Causes*	*Inspection Methods*
Uniform and localized corrosion	Exposure to corrosive material such as mineral or carbonic acids or aqueous environments, seawater and humid or condensing environments. Damage can be localized over an area and is accelerated by exposure to alternating wet/dry conditions, increases in corrosive specie concentration, temperature, oxygen content of the fluid and the large cathodic/anodic surface area ratios in contact with the fluid.	Visual Inspection (VT), direct measurement (DM) and Ultrasonic Testing (UT)
Pitting	Exposure to corrosive material such as mineral or carbonic acids or aqueous environments, seawater and humid or condensing environments. Damage can be localized over an area or uniform distributed surface in contact with the aqueous phase. Corrosion rates can be much higher than uniform or localized corrosion.	VT, DM
Crevice corrosion	Electrochemical concentration cell set up associated in crevice areas with stagnant aqueous phase fluids, such as under sludge, sand, biological materials or corrosion products, failed coatings, gasket surfaces, bolt heads and riveted lap joints. Damage is usually found within the crevice area.	VT and DM
Erosion	High fluid velocity in piping or impingement on a surface, accelerated by solids in the stream	VT, UT and Radiography Testing (RT)
Fatigue cracking	Cyclic loading coupled with an initiating location caused by a stress riser, weld defect, arc strike, mechanical, corrosion damage or environmentally-induced cracking	Surface flaw detection, UT flaw methods, RT
Environmentally induced cracking	Exposure to specific agents that cause environmentally-induced cracking such as caustic and aqueous phases with hydrogen sulfide	Surface flaw detection, UT flaw methods, RT
Creep	Temperature exposure coupled with appropriate stress damage is exposure time dependent, for most steels short term exposure generally above 1200°F is of concern	VT and DM
High temperature oxidation and Metallurgical Changes	Prolonged temperature exposure generally above 1000°F, damage is exposure time dependent, or rapid cooling from above 1300°F in a fire situation.	VT, DM and metallographically, PMI
Brittle Fracture	Low temperature exposure and appropriate stress condition, either applied or from thermal stresses. Enhanced by internal or external defect.	None, inherent property of material, enhanced by external and internal defects
Mechanical damage	Impact or abrasive loading	VT, RT

(Resource: ABS, 2003)